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Civilian Radioactive Waste Management System
Management & Operating Contractor

Modeling for Airborne Contamination

TDR-WER-NU-000001 REV 00

August 2000

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ACRONYMS, UNITS OF MEASURE, AND MATHEMATICAL OPERATORS

Acronyms

ALI	Annual Limit on Intake
BWR	Boiling Water Reactor
DAC	Derived Air Concentration
DBE	Design Basis Event
DCF	Dose Conversion Factor
DP	Development Plan
EDA	Enhanced Design Alternative
MGR	Monitored Geologic Repository
NA	Not Applicable
NRC	U.S. Nuclear Regulatory Commission
PC	Personal Computer
SNL	Sandia National Laboratories

Units of Measure

Bq	becquerel
Ci	curie
cm	centimeter
g	gram
hr	hour
keV	thousand electron volts
μCi	microcurie
μm	micrometer, micron
m	meter
MeV	million electron volts
mrem	millirem
MTU	metric tons uranium
MWd	megawatt-day
pCi	picocurie
rem	roentgen equivalent in man
s or sec	second
Sv	sievert

Mathematical Operators

$$\frac{\partial}{\partial t}, \frac{\partial}{\partial x}$$

are partial differential operators with respect to the indicated coordinate

$$\frac{d}{dx}$$

is the differential operator with respect to the x coordinate

$$\begin{bmatrix} A_{1,1} & A_{1,j} & A_{1,c} \\ A_{i,1} & A_{i,j} & A_{i,c} \\ A_{r,1} & A_{r,j} & A_{r,c} \end{bmatrix} \begin{bmatrix} B_1 \\ B_j \\ B_c \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{c} A_{1,j} B_j \\ \sum_{j=1}^{c} A_{i,j} B_j \\ \sum_{j=1}^{c} A_{r,j} B_j \end{bmatrix}$$

is multiplication between matrix A and matrix B. The number of columns (c) in matrix A must match the number rows (r) in matrix B. The resulting matrix will have the same number of rows as matrix A and the same number of columns as matrix B. The subscript i takes on values of 1, 2,..., r; the subscript j takes on values of 1, 2,..., c. For example, multiplication between a 4r x 2c matrix and a 2r x 3c matrix results in a 4r x 3c matrix.

$$\big|_{x} \text{ or } \big|_{x+\Delta x}$$

the vertical line indicates the boundary condition at which a variable to the left of the line is evaluated.

1. OBJECTIVE AND SCOPE

The objective of *Modeling for Airborne Contamination* (referred to from now on as "this report") is to provide a documented methodology, along with supporting information, for estimating the release, transport, and assessment of dose to workers from airborne radioactive contaminants within the Monitored Geologic Repository (MGR) subsurface during the pre-closure period.

Specifically, this report provides engineers and scientists with methodologies for estimating how concentrations of contaminants might be distributed in the air and on the drift surfaces if released from waste packages inside the repository. This report also provides dose conversion factors for inhalation, air submersion, and ground exposure pathways used to derive doses to potentially exposed subsurface workers.

The scope of this report is limited to radiological contaminants (particulate, volatile and gaseous) resulting from waste package leaks (if any) and surface contamination and their transport processes. Neutron activation of air, dust in the air and the rock walls of the drift during the preclosure time is not considered within the scope of this report. Any neutrons causing such activation are not themselves considered to be "contaminants" released from the waste package. This report:

- Documents mathematical models and model parameters for evaluating airborne contaminant transport within the MGR subsurface

- Provides tables of dose conversion factors for inhalation, air submersion, and ground exposure pathways for important radionuclides.

The dose conversion factors for air submersion and ground exposure pathways are further limited to drift diameters of 7.62 m and 5.5 m, corresponding to the main and emplacement drifts, respectively. If the final repository design significantly deviates from these drift dimensions, the results in this report may require revision. The dose conversion factors are further derived by using concrete of sufficient thickness to simulate the drift walls. The gamma-ray scattering properties of concrete are sufficiently similar to those of the host rock and proposed insert material; use of concrete will have no significant impact on the conclusions.

The information in this report is presented primarily for use in performing pre-closure radiological safety evaluations of radiological contaminants, but it may also be used to develop strategies for contaminant leak detection and monitoring in the MGR.

Included in this report are the methods for determining the source terms and release fractions, and mathematical models and model parameters for contaminant transport and distribution within the repository. Various particle behavior mechanisms that affect the transport of contaminant are included. These particle behavior mechanisms include diffusion, settling, resuspension, agglomeration and other deposition mechanisms.

Some of the transport models may be extended to non-radiological contaminants. For consistency, *activity* units are used in this report for radiological analyses. For non-radiological calculations, these units may be replaced by appropriate *mass* units.

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2. QUALITY ASSURANCE

This document serves as a guide for the performance of calculations affecting radiological aspects of health and safety. This report follows the *Development Plan (DP) Checklist and Cover Sheet for Modeling for Airborne Contamination* (CRWMS M&O 1999a). This report is written in accordance with AP-3.11Q, *Technical Reports*.

An activity evaluation (CRWMS M&O 1999b) has been performed in accordance with procedure QAP-2-0, *Conduct of Activities*. While QAP-2-0 has been superceded by AP-2.21Q, *Quality Determinations and Planning for Scientific, Engineering, and Regulatory Compliance Activities*, this evaluation remains in effect. It has determined that the activities addressed in this report are subject to the requirements of the Quality Assurance Requirements and Description (DOE 2000, Section 2.0), since this report affects items on the Q-List (YMP 2000, Section 4.0).

The application of methodologies and tabulated data in this report concerns MGR radiological control/safety as well as subsurface worker health and safety. Therefore, this report is subject to technical baseline change in accordance with items 5.2d 3) and 4) of AP-3.11Q. A Technical Change Request (T1999-0098) has been prepared in accordance with AP-3.4Q, *Level 3 Change Control*.

Electronic control of data used to generate the results presented in Section 6.8 is maintained by means of a read-only access CD-ROM disk containing the electronic input and output files. This CD-ROM is included as part of this report in Appendix E.

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3. METHOD

The method used in the development of this report was to initially perform an extensive literature review of currently established methods related to potential contaminant release and transport within an enclosed facility similar to that of a repository drift. Relevant information, analytical and numerical models and model parameters, in addition to useful data pertaining to potential airborne release and transport of radioactive materials within the MGR, were identified and documented.

Consideration was given to specific particle behavior mechanisms and associated data that are important to the solution of the evaluation equations for contaminant transport processes. Particle behavior mechanisms include diffusion, deposition, settling, resuspension and agglomeration. Physical, chemical and environmental conditions that influence these particle behavior mechanisms during transport inside the MGR were identified and summarized.

Figure 1 identifies the major steps required to perform a radiological assessment for individuals that may be potentially exposed to airborne and surface contamination inside the MGR. The process starts with the identification of the source and release mechanisms, continues with the evaluation of transport mechanisms, and ends with the pathway-specific dose assessment at the receptor location. The intermediate step of deriving air and surface concentrations may be useful in proper instrument selection and determining appropriate monitoring and control strategies.

The methods recommended for estimating contaminant releases from a waste package, transport within the repository network, and exposures to workers in the repository are summarized as follows:

- Identify the potential source terms and release models (Subsections 6.2 and 6.3).

- Identify the transport mechanisms and resuspension of the released material (Subsections 6.4 and 6.5).

- Formulate analytical models appropriate for estimating contaminant concentrations (Subsection 6.6.1 and Appendix A).

- Identify existing computer codes that may be applicable to the contaminant transport analyses within the repository (Subsection 6.6.2).

- Derive and tabulate drift-specific dose conversion factors (DCFs) for submersion in a cloud of airborne radionuclides and exposure to radionuclides deposited on drift surfaces (Subsection 6.8 and Appendixes B and C).

- Tabulate inhalation DCFs for airborne radionuclides and protection factors afforded by different types of respiratory protection equipment (Subsection 6.9 and Appendix D).

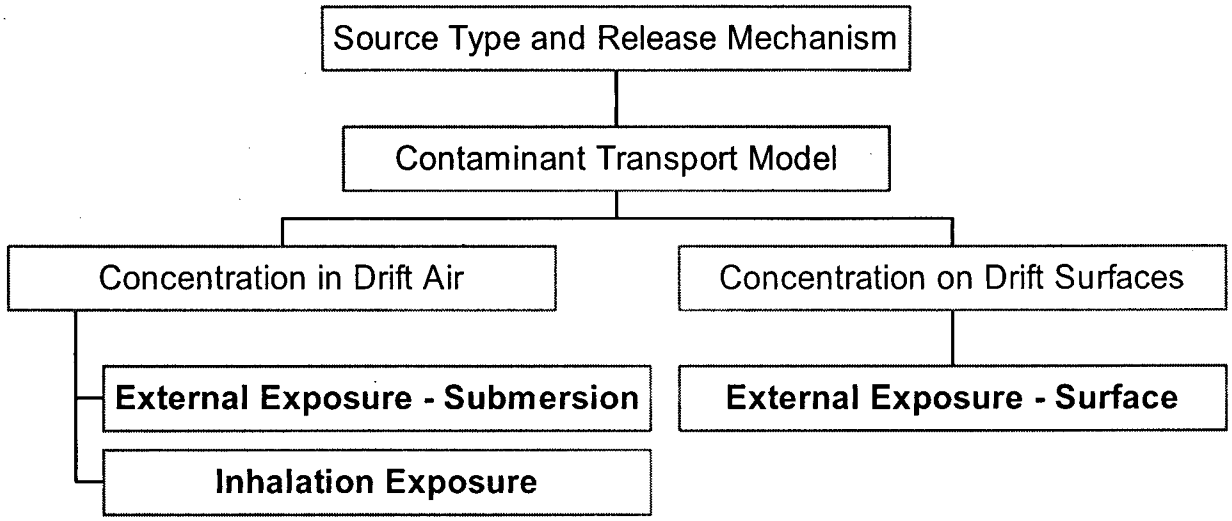

Figure 1. Steps for Performing a Radiological Assessment of Airborne and Deposited Contamination

4. DESIGN INPUTS

Design data and information inputs related to source term development and contaminant transport are for guidance only; such inputs are provided for reference in Section 6.2 of this report. Data and methods used to derive submersion and surface exposure dose factors consist of approved or controlled sources, accepted data, or accepted engineering practice and do not require to be tracked as To Be Verified per AP-3.15Q, *Managing Technical Product Inputs*. The design inputs will require subsequent qualification before this report can be used to support procurement, fabrication, or construction activities. These data are provided as part of this report's primary function to assist future design analyses related to waste package leak detection, radiation monitoring and safety evaluation. The values provided herein are for physical and environmental conditions to be expected in the preclosure phase of the repository.

4.1 DESIGN PARAMETERS

The design parameters used in the calculation of external dose from airborne contaminant releases are identified and provided in the following subsections. All of the following inputs are used in Section 6.8 and Appendixes B and C for the derivation of external dose conversion factors for air submersion and surface contamination in the main and emplacement drifts.

4.1.1 Not Used

4.1.2 Composition of Concrete

The density and elemental compositions of concrete are defined in Table 5.1 of ANSI/ANS-6.4-1985, and is listed in Table 1 of this report. Dividing the partial density of each element with the density of cured concrete (2.35 g/cm3) leads to the weight percent for each element. Example: For H, wt% = (0.013/2.35) x 100 = 0.55.

4.2 CRITERIA

There are no criteria applicable to this report.

4.3 ASSUMPTIONS

All of the following assumptions are used in Section 6.8 and Appendixes B and C for the derivation of external dose conversion factors.

4.3.1 Composition of Air

Air is made up of 80 percent nitrogen and 20 percent oxygen by weight, with a density of 0.001225 g/cm^3.

Basis: This air composition is consistent with the values used in previous shielding calculations (CRWMS M&O 1999c, p. 17)

Table 1. Material Data

Material	Density (g/cm^3)	Element	Partial Density (g/cm^3)	Weight Percent
Ordinary (Type 04) Concrete[a]	2.35	H	0.013	0.55
		O	1.171	49.83
		Si	0.742	31.57
		Ca	0.194	8.26
		Na	0.040	1.70
		Mg	0.006	0.26
		Al	0.107	4.55
		S	0.003	0.13
		K	0.045	1.91
		Fe	0.029	1.23

NOTES: [a] Source: ANSI/ANS-6.4-1985, Table 5.1.

4.3.2 Drift Geometry

Repository drifts are cylindrical in geometry.

Basis: The tunnel-boring machines produce cylindrical drifts; the addition of ground support will not change the basic shape of the drifts.

4.3.3 Particle Deposition

Deposition of particles occurs uniformly on drift surfaces.

Rationale: High ventilation rates and small airborne particle sizes result in uniform deposition on all drift surfaces rather than the gravitational (downward) settling prevalent for larger particles under low air flows.

4.3.4 Receptor Location

The receptor is located at the midpoint of a main or emplacement drift, 1 m above the floor, facing the axis of the drift.

Basis: This location is consistent with the standard dose factors derived by Eckerman and Ryman (1993, p. 18) and will result in the most conservative dose.

4.4 CODES AND STANDARDS

The following codes and standards appear in this report:

- 10 CFR (Code of Federal Regulations) 20. Energy: Standards for Protection against Radiation.

- ANSI/ANS-6.1.1-1977. *Neutron and Gamma-Ray Flux-to-Dose-Rate Factors, an American National Standard.*

- ANSI/ANS-6.1.1-1991. *Neutron and Gamma-Ray Fluence-to-Dose Factors, an American National Standard.*

- ANSI/ANS-6.4-1985. *Guidelines on the Nuclear Analysis and Design of Concrete Radiation Shielding for Nuclear Power Plants, an American National Standard.*

5. USE OF COMPUTER SOFTWARE AND MODELS

5.1 SOFTWARE APPROVED FOR QA WORK

The SCALE code, version 4.3 (SCALE V4.3V), is the computer code used to perform the gamma-ray fluence calculations that are used to derive the dose conversion factors tabulated in Section 6.8. SCALE V4.3V has been fully qualified and baselined on the personal computer (PC) platform (CRWMS M&O 1998a). The code was obtained from the Software Configuration Secretariat and installed on a DELL Precision 410 desktop PC (CRWMS-M&O Tag Number 114419) in accordance with AP-SI.1Q, *Software Management*. This computer has been qualified to perform execution of the SCALE V4.3V software used in this report. The use of SCALE V4.3V in this report is appropriate per the applications and capabilities of the code, and is used within the range of validation in the software qualification report.

SCALE V4.3V is a system of codes for neutron and gamma transport with applications in criticality and shielding analysis. In this report, only the gamma-ray transport features are implemented. First the NITAWL-II module is used to generate cross-section data for air and concrete. These data are then used in the XSDRNPM module with a one-dimensional fixed-source calculation of the gamma-ray fluences used to derive the radiation dose rates. A one-dimensional calculation is appropriate in this case because the main and emplacement drifts of the MGR will be very long relative to their diameters and can be treated as essentially infinite one-dimensional volumes in cylindrical geometry.

A representative input file listing for SCALE V4.3V input used to perform this calculation is included in Appendix B. The full set of input and output files is stored on an electronic medium and is included as part of Appendix E.

The MCNP code, version 4B2 (MCNP V4B2LV), is the computer code used to independently confirm the results of the SCALE V4.3V code. MCNP V4B2LV has been fully qualified and baselined on the PC platform (CRWMS M&O 1998b). The code was obtained from the Software Configuration Secretariat and installed on a DELL PowerEdge 2200 desktop PC (CRWMS-M&O Tag Number 112111) in accordance with AP-SI.1Q, *Software Management*. This computer has been qualified to perform execution of the MCNP V4B2LV software used in this report. The use of MCNP V4B2LV in this report is appropriate per the applications and capabilities of the code, and is used within the range of validation in the software qualification report.

MCNP V4B2LV is a Monte Carlo n-particle code used in this report to estimate the air submersion and surface exposure dose to a receptor located in an emplacement drift. The calculated radionuclide-specific values are used for comparison and confirmation with the same values calculated using the SCALE V4.3V code, providing further confidence in the results.

A representative input file listing for MCNP V4B2LV input used to perform this calculation is included in Appendix B. The full set of input and output files is stored on an electronic medium and is included as part of Appendix E.

5.2 OTHER SOFTWARE USED FOR QA WORK

In addition to the software described in Section 5.1, Microsoft Excel 97 was used as a spreadsheet for reduction of the SCALE V4.3V fluence output and conversion of fluence to dose, implementing the equations presented in Section 6.8. Simple calculations were performed by Excel 97 and checked by hand. A hard copy of the Excel 97 calculations and a description of the user-defined formulas are included in Appendix C. The electronic versions of the Excel 97 files are included in Appendix E. The correct implementation of the equations and the results of these calculations have been verified with a sample hand-calculation presented in Section 6.8. The results of sensitivity analyses and alternate calculation methods presented in Appendix C provide additional confidence in the validity of the results presented in Section 6.8.

5.3 CITED SOFTWARE

Several computer codes are cited and described in Section 6.6.2 of this report. These codes have not been used to derive any of the results in this report, but are presented for information to the reader regarding codes that may have applications to the modeling of airborne contamination. These codes have not completed qualification per AP-SI.1Q, but will require such qualification to be completed prior to their use in quality-affecting work.

5.4 MODELS

No models as defined in AP-SI.1Q, *Software Management,* were used in this report.

6. ANALYSIS

6.1 BACKGROUND

The methodologies that may be applied to contaminant transport analysis within the MGR are presented in this chapter. In section 6.2, contaminant source types and release fractions in the waste packages are identified, and methods that may be used to determine source terms are presented. In section 6.3 through 6.7, methods that may be used to estimate contaminant dispersion and deposition, including simple (hand calculation) models and more complicated computer codes, are presented. The procedures for evaluating the transport of any airborne contaminant through the repository's ventilation system are described. The repository's ventilation system is the primary pathway for release of any contaminants from waste packages to the external environment. In section 6.8, the calculation methodology is presented and dose conversion factors are derived from standard factors to account for the cylindrical geometry of the drifts. In Section 6.9, the calculation methodology and dose conversion factors for inhalation are presented. Both external and inhalation dose calculations should be used in estimating the dose to sub-surface workers from airborne and deposited radioactive contamination.

It is recommended that a review of the data and methodology be conducted prior to using any of the methods and/or dose factors presented in this chapter to determine whether more current information is available.

6.2 CONTAMINANT SOURCE TYPES AND QUANTITIES

This section describes the method that may be used to estimate the amount of material that may be released from a waste package during the preclosure phase of the repository. The method follows, primarily, the information and methodology described in reports published by Sandia National Laboratories (SNL) (Sanders et al. 1991; Sandoval et al. 1991).

Table 2 presents the airborne release fractions used to perform consequence analyses for design basis events (DBEs). These gases, volatiles and particulates are representative of types of radioactive material that could be potentially released to the interior of a waste package. However, the analyst should take care to use the release fractions that are applicable to the situation being analyzed and/or release fractions that are consistent with other analyses being performed for the MGR. The release fraction, except for CRUD, is a fraction of total nuclide inventory within a spent fuel rod, and is applicable only to the failed fuel rods in a waste package. CRUD is a mixture of reactor primary cooling system corrosion products that have deposited on fuel rod surfaces. The release fraction for CRUD is applicable to total estimated CRUD inventory in a waste package. Particulate is used here to represent all other solid fission products and actinides in the spent fuel. Release fractions listed are conservative values used for DBE consequence analyses (CRWMS M&O 1997, Table 4.1-1). As recommended in CRWMS M&O (1999d), DBE analyses of commercial spent nuclear fuel will use release fractions and respirable fractions given in Table 8-1 of CRWMS M&O (1999d).

Table 2. Airborne Release Fractions by Radionuclide Group[a]

Radionuclide Group	Release Fraction
Tritium (H-3)	0.30
Noble Gas (Kr-85)	0.30
Iodine (I-129)	0.10
Cesium (Cs-134, Cs-137)	2.3×10^{-5}
Strontium (Sr-90)	2.3×10^{-5}
Ruthenium (Ru-106)	1.5×10^{-5}
CRUD (Co-60)	0.15
Particulates	2.3×10^{-5}

NOTE: [a] Source: CRWMS M&O 1997, Table 4.1-1.

The source term is the amount of dispersible radioactive species within the waste package that is available for release. An example of a source term calculation is given in CRWMS M&O (1998c, Tables 1 through 3). There are three sources of radioactivity in a loaded waste package:

- The radionuclides contained within the individual fuel rods comprising the fuel assemblies
- Activated corrosion products, referred to as CRUD, adhering to the surface of spent fuel rods
- Residual loose contamination from the above sources that may build up in the cavity of a waste package over time.

All of these three types of radioactive materials may be mobilized during emplacement operations or as the result of an abnormal event or accident within the repository. If the waste package were to develop a leak, any mobilized particle has the potential for moving with the gas flow to the leak site and out to the environment. To reach the environment, a particle must remain airborne long enough to cross the waste package gas space and it must be small enough to be able to pass through the penetration.

An additional source type may be any residual amount of contamination on the external surface of the waste package that was not removed prior to sub-surface transfer. While this is expected to be an insignificant source of radionuclides when considering an individual waste package, it may become significant when applied collectively to all emplaced waste packages.

6.2.1 Spent Fuel Release

Spent fuel contains the largest potential source of releasable radioactivity. The contribution of spent fuel to the overall leakage rate largely depends upon:

- Its initial condition at the reactor site
- Subsequent fuel rod response to normal or abnormal transportation conditions on the road
- Operational conditions for unloading, re-loading, and transport at various MGR facilities
- Final-emplacement conditions at the emplacement drifts
- Cause of the release.

The type and amount of radioactive materials that may be released from the fuel rod to the cavity of a waste package is governed by fuel cladding failure. The extent and severity of cladding failure is a function of fuel irradiation histories, cask and waste package designs, transport loading and unloading conditions, the transport environment, and other initial conditions.

When a breach is produced in spent-fuel cladding, gases and volatile species present in the plenum at the top of individual rods, in interconnecting spaces between fuel pellets, and between pellets and cladding, escape through the opening. Driven by the high pressure differential that exists between the rod's interior and exterior, radioactive species that are mixed with the gases or become entrained in their flow will escape until the equilibrium pressure is reached. The particle size distributions based on fragments taken from spent fuel pellets irradiated to 6000 MWd/MTU and 29,282 MWd/MTU (Ayer et al. 1988, pp. 4.90 to 4.95) are summarized in Table 3. The cumulative mass fractions of fuel particles with sizes less than 10 μm and 100 μm were found to be less than 0.12% and 1%, respectively. A greater percentage of large particles relative to small particles was found at the higher burnup.

Table 3. Spent Fuel Particle Size Distribution

Particulate Size	Spent Fuel Irradiated to 6,000 MWd/MTU Cumulative Mass Percent[a]	Spent Fuel Irradiated to 29,282 MWd/MTU Cumulative Mass Percent[b]
<10.0 μm Diameter	<0.12 %	<0.01 %
<100.0 μm Diameter	<0.6 %	< 1 %

NOTES: [a] Source: Ayer et al. 1988, pp. 4.92 and 4.93.
[b] Source: Ayer et al. 1988, p. 4.95.

6.2.2 CRUD Release

CRUD is a mixture of reactor primary cooling system corrosion products that have deposited on fuel rod surfaces. These deposits contain neutron-activated nuclides and may also contain fissile particles and fission products. During emplacement operations, CRUD may spall from the rods, become airborne in the waste package cavity, and be released should a leak path develop in the waste package containment system. The release rate is dependent on the properties of the CRUD in terms of its specific activity, radioactive species, amount of CRUD available for release, spallation properties, leak rate, and particle size distribution.

The CRUD activity inventory, as discussed in Sandoval et al. (1991), is a function of fuel type, fuel age, isotope composition, and reactor system chemistry. The CRUD spallation rate and initial particle size distribution of dispersed CRUD are functions of initial event conditions, fuel type, and fuel history. The leakage rate is dependent on waste package design in terms of waste package cavity dimensions and configuration, number and type of fuel assemblies in the package, surface area of the cavity, basket, fuel rods, etc.

There are two types of CRUD: a fluffy, easily removed CRUD composed mostly of hematite that is usually found on boiling water reactor (BWR) rods, and a tenacious type occurring on pressurized water reactor rods. The specific nuclides, which are primary contributors to the CRUD total activity, depend on the time since discharged from a reactor. For shipments of 5 years or older fuel, Co-60 accounts for over 92% of the activity in pressurized water reactor fuel and 98% of the activity in BWR fuel (Sandoval et al. 1991, pp. 14 and 15). Therefore, the CRUD activity levels will decrease over time primarily as a function of the Co-60 half-life.

The concentration of CRUD suspended in the cavity of a loaded waste package will depend on the amount of CRUD initially adhering to the fuel assemblies, on the fraction spalled during emplacement operations, and on depletion and resuspension mechanisms acting on the suspended particles. It has been noted that, because of technological improvements in controlling reactor water chemistry for the nuclear industry, most recently discharged fuel has no discernible, or only slight, CRUD deposits (Sandoval et al. 1991, p. 18).

Contrary to the spent fuel case, where only limited data on fuel particle sizes are available, an expected particle size distribution for CRUD was determined based on a CRUD sample on the cladding surface of a Quad Cities fuel rod that is believed to be representative of BWR fuel. The CRUD particle size distribution and density are summarized in Table 4. The particle size distribution was found lognormal in shape with geometric mean diameter equal to 3 μm and standard deviation of 1.87 μm (Sandoval et al. 1991, p. 24).

Table 4. CRUD Particle Size Distribution and Density

Parameter	Value
CRUD particle size distribution[a]	Lognormal distribution with number mean diameter = 3 μm and standard deviation = 1.87 μm
CRUD particle material density[b]	5.2 gm/cm^3

NOTES: [a] Source: Sandoval et al. 1991, p. 24.

[b] Source: Sandoval et al. 1991, p. 33.

6.2.3 Residual Contamination Release

During the spent fuel emplacement operations, the interior surfaces of waste packages may be contaminated with residual radioactive material by impact dislodging and mobilization because of loading and transport operations. After waste packages have been placed inside the drift, radioactive contaminants may build up on the internal surfaces of the waste packages as residual contamination from CRUD spalled off the fuel assemblies, or from fuel fines as a result of diffusion and leaching processes. Based on data collected from the interior deposits of spent fuel shipping casks, it is expected that the primary source of this residual contamination inside the waste packages would be those of Co-60 (Sanders et al. 1991, p. 17). As is the case for the primary CRUD source, the activity of this secondary source is will change over time primarily as a function of the Co-60 half-life, but will also depend on the rate of spallation from the primary source.

The methodology used by SNL to estimate the released activity concentration in cask cavity from the residual contamination is the same as that developed for CRUD. The same particle size distribution developed for CRUD was used for residual contamination (Sanders et al. 1991, pp. 26 and 27).

6.3 WASTE PACKAGE RELEASE

Radioactive materials can be released into the environment external to a waste package only if radionuclides are first released to the waste package cavity or interior surfaces and subsequently escaped from the surfaces and cavity to the external environment. The first phase is governed by the deposition and surface release characteristics of the particulates involved, while the second phase is governed by the characteristics of both the material released to the cavity and the pathway (by a driving force) through the waste package to the external environment. The leak rate, or L (cm^3/sec), can represent the pathway through the waste package cavity to the external environment. A realistic estimate of leak rate requires the development of detailed contaminant release mechanisms and particle transport behavior within the waste package. The detailed development of these parameters is beyond the scope of this report. However, a simpler semi-empirical model provided by the U.S. Nuclear Regulatory Commission (Ayer et al. 1988, p. 4.53) that may be used for estimating the leak rate is included in section 6.3.1. The source term for a release of respirable radioactive material may be estimated in terms of the product of the material at risk, the damage ratio, the airborne release fraction, the respirable fraction, and the leak path factor. These terms and their applications in a design analysis are discussed in detail in *Commercial SNF Accident Release Fractions* (CRWMS M&O1999d). However, when used in accident calculations, release fractions are by necessity conservative, and some of the recommended factors (e.g. damage ratios and leak path factors set to unity) may not be appropriate when designing a monitoring system for detecting airborne contamination.

6.3.1 Release Models

With the exception of gaseous radionuclides such as tritium, Kr-85 and I-129, all radioactive products released from a failed waste package will primarily be in particulate form. Unless the waste packages are severely damaged, these particulates can generally be released in small sizes (i.e., less than a few microns). Radioactive particles may become airborne in several ways.

Rupture of waste package primary barriers can cause release of inventories and radioactive material, some of which may be aerodynamically entrained. Radioactive particles or CRUD containing powders can be released and entrained before particles hit the floor, or resuspended from the floor after a release or leak.

The fraction airborne and size distribution of aerosols produced from pressured or pressure induced releases of powders has been documented by Ayer et al. (1988, p. 4.53) based on experimental data.

The equation, correcting a typo in the original source where 10^4 should actually be 10^{-4}, is:

$$F = 10^{-4}\, V_0^{\,1.4} \qquad \text{(Eq. 1)}$$

where

F = mass fraction airborne
V_0 = initial velocity (m/s)

The initial velocity may be estimated by Ayer et al. (1988, p. 4.55):

$$V_0 = \left(\frac{2PV_t}{m}\right)^{1/2} \qquad \text{(Eq. 2)}$$

where

P = differential pressure at release
V_t = void space in the container
m = total mass of powder (particles) and gas in container

The differential pressure at release may be calculated by:

$$P = P_t - P_d \qquad \text{(Eq. 3)}$$

where

P_t = pressure inside the waste package at the time of release t
P_d = pressure of the emplacement drift

P_t can be calculated using the ideal gas law:

$$P_t = \frac{P_0 T_t}{T_0} \qquad \text{(Eq. 4)}$$

where

P_0 = pressure inside the waste package at the time spent fuel is loaded
T_t = temperature inside the waste package at the time of release

T_0 = temperature inside the waste package at the time spent fuel is loaded

Using the calculated initial velocity, the initial leak rate L_0 can be calculated by:

$$L_0 = V_0 W \quad \text{(Eq. 5)}$$

where

L_0 = initial leak rate (m^3/s)
W = area of the leak path (m^2)

6.3.2 Duration of Release

The duration of release for contaminants could vary considerably depending on the specific mechanism causing a waste package to rupture. Under extensive damage situations, the duration of a release can be instantaneous, or range from several hours to days before response actions control the situation. Response actions such as waste package retrieval can also contribute to the release. In *Design Basis Event/Scenario Analysis for Preclosure Repository Subsurface Facilities* (CRWMS M&O 1997, Section 4.3.4), contaminants were assumed to be released instantaneously for a mechanistic DBE. For a non-mechanistic DBE, a release was assumed to last for two hours (CRWMS M&O 1997, Section 4.3.3).

6.4 PARTICLE TRANSPORT MECHANISMS

Once the released small particles become airborne, the movement of these particles is largely dependent on the vertical turbulence. This turbulence is due to the natural convection caused by the temperature gradient between the waste package and the air interfaces coupled with the mean motion of the air generated by the ventilation flow. Deposition of these particles onto surfaces is the result of turbulent and molecular diffusion, gravitational settling, impaction and other physical and chemical processes that can cause the material to be retained at the surface. These deposition mechanisms deplete the amount of airborne radioactivity, thus affecting the potential hazards as the contaminant particles travel farther downstream from the release point.

6.4.1 Deposition Velocity

The concentration of airborne contaminants is depleted by various particle mechanisms that include the processes of molecular diffusion, gravitational settling, impaction, particle interception, and other physical and chemical absorption processes (see Table 5).

The depletion processes result in a reduction of the initial source strength at increasing downstream distances from the emission point. Total deposition is generally calculated from an empirically determined parameter, the deposition velocity, V_d, defined as the ratio of the deposition rate, D_p, to the air concentration, C_a, at ground-level (Slade 1968, p. 204). Mathematically, V_d is written as:

$$V_d = \frac{D_p}{C_a} \quad \text{(Eq. 6)}$$

where

V_d = deposition velocity (m/s)
D_p = deposition rate (pCi/m^2/s)
C_a = air concentration (pCi/m^3)

Table 5. Particle Behavior Mechanisms

Mechanism	Description	Influencing Parameters	Slinn's Deposition Model[a]	Computer code MSPEC[b]
Diffusion	Movement of particle due to random gas molecular collisions and microscopic eddies in air	Particle size, Density, Temperature	Yes	Yes
Settling	Effect of gravity upon airborne particles	Particle size, Density, Flow velocity	Yes	Yes
Agglomeration	The adherence of a particle to another upon collision to produce a particle of larger size	Particle size, Number of particles, Eddy velocity	No	Yes
Thermophoresis	Movement of particles caused by a temperature gradient	Temperature gradient	No	Yes
Diffusiophoresis	Movement of particles caused by concentration gradients in gas phase	Vapor condensation rate	Yes	No
Impaction	Absorption of particles by inertial impaction	Flow velocity, Surface roughness	Yes	No

Note: [a]Source: Slinn 1977, pp. 530 to 532

[b]Source: Jordan et al. 1982. See Section 6.6.2.2 for discussion of the MSPEC computer code.

Since deposition rate or velocity is usually determined by measurements, for an accurate estimate of deposition processes the repository-specific deposition velocity must be determined first. At present, data for estimating the site-specific deposition velocity have not been obtained; therefore, a semi-empirical model, which compared reasonably well with experimental data, is provided in this report. This semi-empirical model is the deposition velocity equation derived for smooth surfaces by Slinn (1977, pp. 530 to 532). Slinn's deposition velocity equation is comprehensive; it includes terms for molecular diffusion, gravitational settling, inertial impaction, and diffusiophoresis. The equation has the following form (Slinn 1977, pp. 531):

$$V_d = V_s + 10^3\,\mathrm{cm/sec}\left(\frac{m''}{1\mathrm{g/cm^2/sec}}\right) + \frac{U_*^{\,2}}{\beta\bar{U}}E_j \qquad \text{(Eq. 7)}$$

where V_s is the particle's settling velocity, m" is the water vapor flux, and E_j is the collection efficiency and is expressed as:

$$E_j = 10^{-3/St} + \frac{\beta}{\gamma}(Sc)^{-0.6} \qquad \text{(Eq. 8)}$$

in which:

$$St = \frac{\tau U_*^2}{\nu} \qquad \text{(Eq. 9)}$$

is the particle's Stokes number based on the characteristic velocity U_* and the viscous length scale ν/U_*. τ is the particle's relaxation time and ν is the kinematic viscosity of air, $Sc = \nu/D$ is the Schmidt number and D is the particle's diffusion coefficient. In Equations 7 and 8, β and γ are empirical constants. $\beta = \gamma = 0.4$ were used by Slinn to compare experimental data points taken in the field (Slinn 1977, pp. 531 and 532). The results of the comparison between Equation 7 and the measurements were in good agreement.

In Equation 7, the settling velocity V_s, for particle Reynolds number ranging between 10^{-4} and 10 and neglecting the effect of slip flow, may be calculated by the Stokes equation (Slade 1968, p. 202):

$$V_s = \frac{\rho_p d_p^2 g}{18\mu} \qquad \text{(Eq. 10)}$$

where

d_p = particle diameter
ρ_p = particle density
g = gravitational acceleration
μ = fluid viscosity

The effect of the slip flow upon V_s is a function of the ratio of the mean free path of the air molecules to the particle size. It can be expressed by multiplying V_s by a slip correction factor C_{slip} (Slade 1968, p. 202) as follows:

$$C_{slip} = 1 + \frac{\lambda}{r}\left[1.26 + 0.4e^{-\left(\frac{1.1r}{\lambda}\right)}\right] \qquad \text{(Eq. 11)}$$

where

λ = mean free path of air molecules
r = particle radius

6.5 RESUSPENSION

Airflow over surface deposited materials can entrain particles, making them airborne in a process known as resuspension. The resuspension mechanisms can occur over any natural or artificial surfaces from which particles may be detached by the flow of air or other disturbance. The concentration of particles resuspended in air is dependent on many factors, including:

- Geometrical configuration and property of the surface
- Speed of the flow
- Characteristics of the deposited particulate
- Disturbance by human or natural activities
- Time since deposition.

The time factors that may be important include:

- Weathering processes that alter the physical and chemical states of the contaminant
- Attachment to host particles
- Downward migration by physical and chemical processes
- Redistribution of material deposited on the surface.

The amount of contaminant that is resuspended into the air may be estimated using two different factors: resuspension factor or resuspension rate. Resuspension factor (in units of m^{-1}) converts surface concentration into air concentration above the contaminated surfaces, while resuspension rate (in units of sec^{-1}) converts contaminant surface concentration into surface flux.

6.5.1 Resuspension Factor

The resuspension factor, K, is the ratio (in units of m^{-1}) of the concentration in the air at a reference height to the contamination per unit area on the surface. The concentration of a contaminant in the air is related to the resuspension factor by:

$$C_R = K\,C_s \qquad \text{(Eq. 12)}$$

where

C_R = resuspended air concentration (pCi/m^3)
K = resuspension factor (m^{-1})
C_s = surface deposited concentration (pCi/m^2)

Experimentally determined resuspension factors have been recorded for various particulate materials from various surfaces. Sutter (1982, pp. 2.13 and 2.14) has summarized tabulated ranges of resuspension factor (K) that were compiled from numerous observations. Some of the K values that may be applicable to the MGR are listed below in Table 6. The resuspension factors range from 2.0×10^{-8} m^{-1} inside a room with no movement to 4.0×10^{-2} m^{-1} for an unventilated room under vigorous sweeping.

For contaminant transport calculations within the MGR, resuspension factors are most useful for predicting concentrations of airborne material right above contaminated surfaces. They may also be used to estimate the release rate or total release, if the affected area and volume are known and the duration of the release can be predicted. However, it should be recognized that because of its wide ranges, resuspension factor must be used with caution and based on careful assessment of the source material and the event making the material airborne.

6.5.2 Resuspension Rate

The resuspension rate is the fraction of the resuspendable contamination that becomes airborne per unit time, usually expressed in units of s^{-1}. Experimentally measured resuspension rates for particles with aerodynamic equivalent diameters of 10 μm or less at two airflow velocities in a wind tunnel (Sutter 1982, p. 2.19) that may be applicable to the MGR are given in Table 7. The aerodynamic equivalent diameter is the diameter of a unit-density sphere that would have the same terminal velocity due to gravity in air as the particle under consideration. The measured resuspension rates were 6.7 x 10^{-6} and 1.2 x 10^{-5} per sec, respectively, for airflow velocities of 1.12 and 8.94 m/s for smooth, sandy soil surface. For a stainless steel surface, the resuspension rates were 2.6 x 10^{-6} and 7.6 x 10^{-6} per sec for flow velocities of 1.12 and 8.94 m/s, respectively. As indicated in Sutter (1982), the resuspension of material is not linear with time; the resuspension rates vary with time of sampling or release.

Table 6. Resuspension Factors from Mechanical Stresses[a]

Location	Source Material	Resuspension Stress	Resuspension Factor Range, m^{-1}
Laboratory room	PuO_2	No Movement	2.0 x 10^{-8}
		Walking	1.0 x 10^{-6} to 5.0 x 10^{-6}
Unventilated room	Beryllium	Vigorous sweeping	1.0 x 10^{-2} to 4.0 x 10^{-2}
Room-concrete floor	Plutonium facility	No circulation	1.0 x 10^{-6} to 2.0 x 10^{-4}
		Fan air stress	3.0 x 10^{-4} to 3.0 x 10^{-3}
		Fan and dolly movement	4.0 x 10^{-3} to 1.5 x 10^{-2}
Room-concrete floor	Uranium facility	No circulation	7.0 x 10^{-5} to 4.0 x 10^{-4}
		Fan air stress	3.0 x 10^{-5} to 2.0 x 10^{-4}
		Dolly movement	1.0 x 10^{-4} to 2.0 x 10^{-4}
		Fan and dolly movement	2.0 x 10^{-4} to 1.0 x 10^{-3}

NOTE: [a] Source: Sutter 1982, pp. 2.13 and 2.14.

Table 7. UO_2 Resuspension Rates from Wind Tunnel Experiment[a]

Surface	Airflow Velocity		Resuspension Rate
	mph	m/s	sec^{-1}
Smooth, Sandy soil	2.5	1.12	6.7 x 10^{-6}
	20	8.94	1.2 x 10^{-5}
Stainless Steel	2.5	1.12	2.6 x 10^{-6}
	20	8.94	7.6 x 10^{-6}

NOTE: [a] Source: Sutter 1982, p. 2.19. Original units (mph) in source multiplied by 0.447 to obtain units of m/s.

6.5.3 Threshold Velocity for Particle Entrainment

Particle entrainment is possible only when particles on the attached surface begin to move. Before particle motion can occur, a threshold airspeed must be equaled or exceeded so that the aerodynamic forces are enough to overcome restraining forces. The airspeed large enough to accomplish this is defined as the threshold airspeed or threshold friction velocity U_{*t}.

To relate threshold airspeed to surface effects, Martin et al. (1983, pp. 15 to 20) developed a model for estimating U_{*t} based on the following friction velocity equation:

$$U_* = \sqrt{\frac{\tau}{\rho}} \qquad \text{(Eq. 13)}$$

where

U_* = friction velocity
τ = mean shear stress at the surface
ρ = fluid density

Martin et al.'s model calculates threshold friction speed using a set of semi-empirical equations derived from experimental measurements. These equations can be used to calculate U_{*t} for a given particulate size and density. However, an iterative technique has to be used because U_{*t} appears implicitly on both sides of the equations. The equations have the following forms, depending on the particle friction Reynolds number B:

for $0.22 \le B \le 10$:

$$A = \left(0.108 + \frac{0.0323}{B} - \frac{0.00173}{B^2}\right)\left(1 + \frac{0.055}{\rho_p g d_p^{\,2}}\right)^{1/2} \qquad \text{(Eq. 14)}$$

where

$$A = \frac{U_{*t}}{\left[(\rho_p - \rho) g d_p / \rho\right]^{1/2}} \qquad \text{(Eq. 15)}$$

$$B = U_{*t} d_p / \nu \qquad \text{(Eq. 16)}$$

d_p = particle diameter
ρ_p = particle density
g = gravitational acceleration
$\nu = \mu/\rho$ = fluid kinematic viscosity
μ = fluid viscosity

For $B \le 0.22$:

$$A = 0.266\left(1 + \frac{0.055}{\rho_p g d_p^{\,2}}\right)^{1/2} (1 + 2.123B)^{-1/2} \qquad \text{(Eq. 17)}$$

Using U_{*t} as a measure of when entrainment is possible, the minimum airflow velocity that can produce a friction velocity U_* exceeding the threshold friction velocity can be calculated. For a given surface condition, the minimum airflow velocity that can produce a friction velocity $U_* \geq U_{*t}$ may be estimated using one of the following two equations given in Martin et al. (1983, p. 18) after substituting U_{*t} for U_*.

For a smooth surface with a laminar sublayer:

$$\frac{U(y)}{U_*} = \frac{1}{0.41}\ln\left(\frac{yU_*}{\nu}\right) + 5.0 \qquad \text{(Eq. 18)}$$

For a rough surface with no laminar sublayer:

$$\frac{U(y)}{U_*} = \frac{1}{k}\ln\left(\frac{y}{y_0}\right) \qquad \text{(Eq. 19)}$$

where

$U(y)$ = airflow velocity at y (cm/s)
y = distance from surface (cm)
k = 0.4 = Von Karman constant
y_0 = R/30 = roughness length (cm)
R = average surface roughness height (cm)

Using the above equations, the ventilation flow rates that could result in the resuspension of surface deposited materials may be estimated if the surface properties of the repository are known.

6.6 CONTAMINANT TRANSPORT MODELS

This section describes the techniques, analytical models, and computer codes that may be used to analyze material transport and aerosol behavior within the MGR in the event that a release of material such as described in Section 6.2.

Two methods of estimating material transport and aerosol behavior are described in the following sections. These are:

A. Analytical Equations - hand calculations that utilize one-dimension models assuming steady state conditions and complete mixing. These equations are primarily concerned with dispersion and deposition of radioactive materials within a repository drift.

B. Computer codes - computer programs that may be adopted to perform a more comprehensive analysis of, under either steady or unsteady state conditions, the dispersion and aerosol behavior of the released radioactive materials within the repository network(s). These computer codes are only summarized here. The detailed descriptions are given in their user's manuals. All of these computer codes will be evaluated further regarding their specific applicability to the MGR subsurface facilities.

6.6.1 Analytical Models

This subsection describes analytical equations or models that may be used for calculating the distribution of contaminant concentrations within the repository network once a release is developed. The analytical equations provided here are based on the assumptions that the release is steady state and contaminants are uniformly distributed in the airflow. The detailed derivation of the models given in this section is provided in Appendix A.

The contaminant activity or mass concentrations in a segment of a tunnel with radius of R along a one-dimensional direction in x can be calculated by applying the law of conservation of mass of contaminant as:

$$C_a(x_2) = C_a(x_1)e^{-k(x_2-x_1)} + \frac{F}{V_r}(1 - e^{-k(x_2-x_1)}) \qquad \text{(Eq. 20)}$$

where

$k = \dfrac{2V_r}{UR}$
F = average contaminant surface flux (pCi/m^2/s)
$V_r = (V_d - V_s/2)$ = contaminant removal velocity (m/s)
V_d = deposition velocity (m/s)
V_s = settling velocity (m/s)
R = drift radius (m)
$C_a(x_2)$ = contaminant air concentration at x_2 (pCi/m^3)
$C_a(x_1)$ = contaminant air concentration at x_1 (pCi/m^3)
U = cross-section averaged ventilation flow rate (m/s)

The surface contaminant concentrations from the released source are calculated from the airborne concentrations and are given by the following equation:

$$C_s = C_a(x)\, V_d\, T_d \qquad \text{(Eq. 21)}$$

where

$C_s(t)$ = contaminant surface concentration at time t = T_d (pCi/m^2)
T_d = time interval over which deposition has occurred (sec)

The detailed derivation of Equations 20 and 21 is provided in Appendix A.

6.6.2 Computer Codes

In the previous section, analytical models have been provided for simple hand calculations. These models are developed to analyze contaminant transport for simple geometric configuration such as a segment of the repository network and are for releases under steady state flow conditions. These models, however, if used with conservative input parameters, may be appropriate for contaminant release consequence analyses, or for comparative analyses of repository design parameters and alternatives.

For releases associated with abnormal events such as pressure transient induced flow, computer codes should be used if detailed and realistic analyses of contaminant transport are desirable. The computer codes that may be suitable for these types of analyses are identified in this section.

6.6.2.1 Ventilation Modeling Computer Code

TVENT1P (Andrae et al. 1984) is a computer code developed to predict net flows, component flows, and pressures in a ventilation system network. TVENT1P is an enhanced version of the TVENT code (Duerre et al. 1978), which is widely used for analyzing ventilation flow due to tornado induced pressure changes. TVENT1P code is similar to TVENT; however, it is more flexible and is applicable to all operational-type ventilation system analyses. The TVENT1P code models actual ventilation system components including dampers, ducts, blowers, filters, and external leak paths. The input of the code defined by the user includes (1) the system description, (2) resistance coefficients, (3) initial boundary conditions, (4) blower curves, (5) filter models, (6) capacities, and (7) transient conditions. The system description required by TVENT1P can be derived from process and flow diagrams of each particular area. Resistance coefficients are used to account for the non-ideal nature of flow through actual systems. These coefficients take into account the variation in flow and differing friction factors associated with the material of construction. TVENT1P allows for input of initial flow rates and pressures through a system, room volume, blower performance curves (flow rate vs. static head), filter models depending upon flow rates, and any transient conditions that might exist, such as a variation in boundary conditions or changing system operation. Initial flow rates, pressures, and volumes are found or calculated from data available in the process area. The equipment manufacturer usually supplies the blower performance curves. An additional factor that must be considered in the filter model input is plugging due to accumulation of material on the filter.

The output provided by TVENT1P allows observation of variations of pressure drops across system elements, flow rates through various branches, and material concentrations, all as a function of time. From this type of data, it is possible to track the material transport from source term generated inside a facility to exhaust from the facility. The TVENT1P code allows many different accident scenarios, single source or multiple source generation, or any combination of the above. The detailed information on TVENT1P is contained in the TVENT1P User's Manual (Andrae et al. 1984).

6.6.2.2 Particulate Deposition Computer Code

The TVENT1P code was developed for ventilation flow analysis and does not include routines for particle deposition analysis as described in Section 6.4. To use TVENT1P for contaminant transport analyses involving deposition mechanisms, a deposition routine needs to be incorporated. The deposition equations (Equations 20 and 21) described in Section 6.6.1 may be adequate in conjunction with the TVENT1P code for estimating particle deposition and surface concentration within a segment of the repository network under steady state conditions. However, for situations involving unsteady state analyses, or for more complete deposition analyses (e.g. thermophoresis and particle agglomeration), a computer simulation code such as the MSPEC code (Jordan et al. 1982) may be required.

MSPEC code estimates aerosol behavior in a homogeneously mixed non-flowing containment atmosphere. The aerosol particles can be characterized by representative particles in each of a finite set of size categories. Each representative particle has the average, time varying characteristics of its size class. The MSPEC code allows for modeling of deposition of particles through sedimentation, diffusion, as well as thermophoresis. Particle agglomeration mechanisms are also modeled in the code. Another unique function of the MSPEC code is that it is capable of modeling a release with several species in the source term. The input required for MSPEC can be entered in the form of distributions instead of single values.

The specific input parameters that the user must define using MSPEC include particle size distribution, up to 10 different species in an aerosol "cloud", aerosol temperature and pressure, deposition surface areas and enclosure volumes. The output is presented to allow direct observation of the mass of the aerosol that is deposited as a result of each deposition mechanism. The total mass deposition at each time step is also given. The output provides detailed data on each separate component including particle size distributions and the mass of each component deposited. The detailed modeling equations and their solution schemes are given in the MSPEC User's Manual (Jordan et al. 1982).

Through the combined use of MSPEC and TVENT1P, it may be possible to track an aerosol release throughout a series of modules, incorporating ventilation flow parameters, aerosol depletion, and concentration variables to present an accurate estimate of particle transport and distribution data within the repository network(s).

6.6.2.3 Generalized Flow, Heat and Mass Transport Code

For contaminant transport analyses involving complex geometry and flow, heat and mass transport phenomena, a generalized computer code such as the ANSWER software program (ACR 1997) may be required. The ANSWER code is a comprehensive computational fluid dynamics software tool for analysis of complicated problems in flow, heat and mass transport. The code provides for coupled transport of fluid, heat and multiple chemical species in complex three-dimensional geometry. According to its User's Manual (ACR 1997), the code is able to simulate the transient or steady state behavior of fluid flow with chemical reactions, combustion, liquid sprays, droplet burning, soot formation, and radiation. It has also been used to analyze, among various fluid flow problems, ventilation of tunnels and HVAC design optimization analyses. The applicability of the code to the flow and mass transport problems associated with the design of the MGR facilities will be evaluated further, if required.

6.7 FILTER EFFICIENCY

In the MGR, flow of air through the repository is mostly determined by the flow rates of the ventilation networks. Depending on the ventilation design, the ventilation system may include filters that remove most of the airborne particles from exhaust air. It is important to determine from the ventilation system attributes whether any potential leaks will be filtered or unfiltered. In case of a filtered release, filter efficiencies will need to be estimated. It should be noted that filters would not remove any gaseous contaminants from the airflow.

6.8 EXTERNAL GAMMA DOSE CONVERSION FACTORS

Releases of gaseous and particulate radionuclides from waste packages may result in external gamma exposures to workers located in the repository drifts. The exposure mode may be submersion in a contaminated cloud of gaseous and particulate radionuclides as well as exposure to contaminated drift surfaces due to deposition of particulate radionuclides. Standard dose coefficients exist to calculate doses from air submersion and surface deposition (Shleien et al. 1998, Tables 13.30.1 and 13.30.3), but these assume submersion in a semi-infinite cloud and contamination on an infinite plane, respectively. The cylindrical geometry of the drifts leads to exposure conditions that are significantly different from the standard exposure assumptions (see Figure 2). The dose conversion factors (DCFs) for air submersion and surface deposition in drifts are listed in Table 8 along with the standard dose coefficients. The DCFs are reported only for those radionuclides that were found to contribute collectively to more than 99.9% of the total effective dose equivalent from air submersion and ground surface exposure following a non-mechanistic DBE (CRWMS M&O 1998c, pp. 13 to 15, Tables 2 and 3). However, the methodology in this section can be easily extended to other gamma-emitting radionuclides.

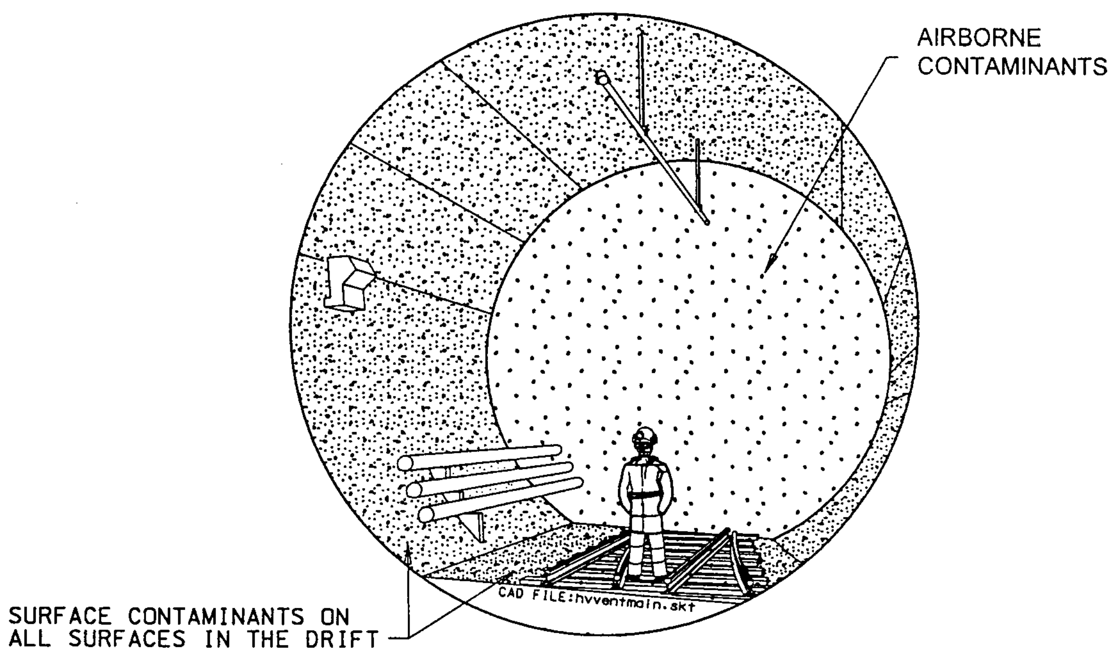

Figure 2. Schematic Diagram of Drift Showing Receptor Location and Contaminant Distribution

The method used in this report to estimate the DCFs for external gamma exposures in the drifts starts with the calculation of the gamma-ray fluences. These fluences are then converted to dose by applying appropriate fluence-to-dose conversion factors. Geometry scaling factors are then derived and applied to the standard DCFs to obtain the geometry-specific DCFs.

A unit source consisting of 18 mono-energetic gamma-ray groups is assumed to be distributed uniformly in the air or on the surface of the drifts. These 18 energy groups cover the range of 10 MeV to 0.01 MeV. The SCALE V4.3V code was used to estimate the fluence of each of the 18 energy groups (including the primary and down-scattered gamma energy groups) at 1 meter above the surface of the drift. Backscattering from the walls of the drift was taken into account, but end effects were conservatively neglected due to the considerable length of the drifts relative to their diameter and the assumption in the model that the receptor is at the midpoint of a drift.

Due to the large number of groups, the runs were performed in 2 parts (energy groups 1-9 and energy groups 10-18) for each condition as follows:

- Air submersion
  - infinite air slab
  - main drift air
  - emplacement drift air

- Ground or drift surface
  - infinite plane
  - main drift surface
  - emplacement drift surface.

The result of the SCALE V4.3V calculations was a set of 18 x 18 energy-dependent fluence arrays (one for each of the six geometries, see Equation 22). The fluence near the air-ground interface from a semi-infinite slab source was approximated by taking one-half that due to the infinite air slab source following the method in Eckerman and Ryman (1993, p. 13).

The fluences were converted to effective dose equivalent conversion factors (see Appendix C for details of the calculations) by applying the fluence-to-dose factors, which were calculated using the polynomial fit coefficients from Table 5 of ANSI/ANS-6.1.1-1991, *Neutron and Gamma-Ray Fluence-to-Dose-Rate Factors*, for the appropriate exposure geometry as follows:

- Semi-infinite slab source – isotropic (ISO, radiation incident from all directions) exposure geometry

- Infinite plane source – rotational (ROT, radiation incident from all sides) exposure geometry

- Contaminated air in drift or contamination on drift surfaces – average of anterior-posterior (AP, radiation incident from front to back) and posterior-anterior (PA, radiation incident from back to front) exposure geometries.

According to Table 3 of ANSI/ANS-6.1.1-1991, the use of fluence-to-dose factors for AP exposure geometry should be used when the geometry is not known, since this would result in the most conservative values. However, this is not a realistic assumption when a receptor is in the middle of a drift since radiation is directed primarily to the front and back of the body when the receptor faces the drift axis. If the receptor were located at the end of a drift, the AP exposure condition may apply, but only half of the source would expose the receptor, reducing the dose by approximately 50%. In any case, the difference between AP and average AP-PA geometries is less than 10% for most energy groups (see Appendix C). The most appropriate exposure geometry for an infinite slab source is ISO geometry, where the incident gamma rays originate from all directions; the conversion to semi-infinite slab geometry effectively eliminates the upward direction, but does not have a significant impact on the resulting doses. The most appropriate exposure geometry for an infinite plane source is ROT geometry, since most of the incident gamma rays originate from all sides of the receptor; only a small fraction originate below the receptor, but do not have a significant impact on the resulting doses.

Equation 22 illustrates the matrix multiplication used to derive the DCFs for each energy group:

$$\begin{bmatrix} DCF_1 \\ DCF_2 \\ \vdots \\ DCF_{18} \end{bmatrix} = \begin{bmatrix} F_{1,1} & F_{1,2} & \cdots & F_{1,18} \\ 0 & F_{2,2} & \cdots & F_{2,18} \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & F_{18,18} \end{bmatrix} \begin{bmatrix} FTD_1 \\ FTD_2 \\ \vdots \\ FTD_{18} \end{bmatrix} \qquad \text{(Eq. 22)}$$

where DCF_i is the dose conversion factor for the i^{th} energy group. $F_{i,j}$ is the fluence calculated by SCALE V4.3V, in photons/cm^2-sec multiplied by 10^6, at one meter above the surface for a source of 10^6 photons in energy group i per cm^3/sec (source in air) or cm^2/sec (source on surface). The index j represents the fluence of uncollided (j=i) photons in group i and the fluence of photons from group i that are scattered into energy groups ranging from j=i+1 to 18. FTD_i is the geometry-specific fluence-to-dose factor (from ANSI/ANS-6.1.1-1991) for energy group i.

For each of the radionuclides in Table 8, the energy-dependent gamma intensities (Kocher 1981, Appendix 5) were multiplied by the corresponding DCFs for the semi-infinite air, infinite plane, or drift geometries as follows:

$$D_{nuclide} = \begin{bmatrix} GI_1 & GI_2 & \ldots & GI_{18} \end{bmatrix} \begin{bmatrix} DCF_1 \\ DCF_2 \\ \vdots \\ DCF_{18} \end{bmatrix} \qquad \text{(Eq. 23)}$$

where $D_{nuclide}$ is the unit dose rate for the specified radionuclide, and GI_i is the sum of the photon intensities emitted by that radionuclide in energy group i.

An example of this calculation is presented for Am-241, a radionuclide that emits three gamma-rays (26.3, 33.2, and 59.5 keV at 2.40%, 0.106% and 35.9% intensity, respectively) and one x-ray (13.9 keV at 43% intensity). The intensities of the x-ray and the first two gamma-rays are summed to 45.5% and accounted for in the 18th energy group (0.01 – 0.05 MeV). The final gamma ray is placed in the 17th energy group at 35.9% intensity. The intensities in all other energy groups are set to zero. Therefore, for purposes of this example, the derived DCFs for energy groups 1-16 will not be shown, and the problem is reduced to the multiplication of 2- and 4-element matrices. From the SCALE V4.3V calculations, the calculation of DCFs for the last two groups for the air submersion semi-infinite slab and main drift air-submersion geometries is performed using Equation 22:

Semi-infinite slab DCFs: $\begin{bmatrix} DCF_{17} \\ DCF_{18} \end{bmatrix} = \begin{bmatrix} 1.44\times10^{6} \\ 4.90\times10^{4} \end{bmatrix} = \begin{bmatrix} \dfrac{3.40\times10^{10}}{2} & \dfrac{1.49\times10^{9}}{2} \\ 0 & \dfrac{2.04\times10^{9}}{2} \end{bmatrix} \begin{bmatrix} 8.28\times10^{-5} \\ 4.80\times10^{-5} \end{bmatrix}$

Main drift submersion DCFs: $\begin{bmatrix} DCF_{17} \\ DCF_{18} \end{bmatrix} = \begin{bmatrix} 8.66\times10^{4} \\ 3.51\times10^{4} \end{bmatrix} = \begin{bmatrix} 6.14\times10^{8} & 7.71\times10^{6} \\ 0 & 3.98\times10^{8} \end{bmatrix} \begin{bmatrix} 1.40\times10^{-4} \\ 8.82\times10^{-5} \end{bmatrix}$

The nuclide-specific unit dose rate, $D_{Am\text{-}241}$, is obtained using Equation 23:

Semi-infinite slab $D_{Am\text{-}241} = \begin{bmatrix} 0.359 & 0.455 \end{bmatrix} \begin{bmatrix} 1.44\times10^{6} \\ 4.90\times10^{4} \end{bmatrix} = 5.41\times10^{5}$.

Main drift submersion $D_{Am\text{-}241} = \begin{bmatrix} 0.359 & 0.455 \end{bmatrix} \begin{bmatrix} 8.66\times10^{4} \\ 3.51\times10^{4} \end{bmatrix} = 4.71\times10^{4}$.

The appropriateness of using the fluence-to-dose factors from ANSI/ANS-6.1.1-1991 (referred to as the 1991 standard) rather than the factors from Table 3 of ANSI/ANS-6.1.1-1977, *Neutron and Gamma-Ray Flux-to-Dose-Rate Factors* (referred to as 1977 standard) is discussed below. The 1977 standard's neutron flux-to-dose factors are used in shielding calculations at the Yucca Mountain Project because they are consistent with the treatment of neutron fluence in 10 CFR 20. By association, the gamma-ray flux-to-dose factors in the 1977 standard have been applied to estimate doses from the primary and secondary gamma-ray fluences from waste packages for the following reasons:

- Consistent: same source as the approved neutron flux-to-dose factors used in the shielding analyses

- Conservative: produces whole body dose equivalents from high-energy gamma rays that are approximately 20% higher than using the 1991 standard fluence-to-dose factors for AP exposure geometry

- Measurable: representative of readings from survey meters or area monitors that measure ambient dose equivalent

- Licensing precedent: the 1977 standard has been successfully applied to shielding analyses for dry storage and transportation casks, which are conceptually similar to shielding analyses for waste package containers and transporters.

Since no shielding is being designed to protect the potential receptors from the gamma rays emitted by airborne radionuclides, and there are no significant neutron-emitting airborne radionuclides, the 1991 standard is more appropriate for this analysis for the following reasons. The radiation is not coming from a single direction, but is dependent on the source geometry and receptor orientation; the 1991 standard includes fluence-to-dose factors for multiple exposure geometries whereas the 1977 standard does not. The DCFs for this report are derived by adjusting standard dose factors (Shleien et al. 1998, Tables 13.30.1 and 13.30.3) for infinite sources by the finite geometry of the source in the main and emplacement drifts. The standard dose factors are derived on the basis of the effective dose equivalent, which takes into account weighting factors for organ doses; the 1977 standard does not take into account the organ-specific radiation sensitivities and absorption properties, but is based on the ambient dose equivalent. The instruments that will be used to detect airborne radionuclides do not measure ambient dose equivalents as is the case for external gamma monitors, but rather the concentrations of radionuclides in air. Since the source is not contained, as would be the case in a shielding analysis, the airborne radionuclides may result in both inhalation and external gamma doses to an individual exposed to this source. Since the inhalation dose factors in 10 CFR 20 are also based on the effective dose equivalent model, the summation of external gamma and inhalation doses can be performed using a consistent methodology to derive the total effective dose equivalent to the receptor. Finally, the application of the 1977 standard results in drift-geometry DCFs for low-energy gamma emitters that are so conservative (well above 20%) that in some cases they exceed the values tabulated for the infinite geometry DCFs. It is important to note that when designing a shield for gamma radiation, the bias is towards the higher end of the energy spectrum, since the shield is much more efficient at reducing the contributions from the low-energy end of the gamma-ray spectrum. However, in the case of airborne and deposited radionuclides, the low-energy gamma emitters are not shielded from the receptor and may contribute significantly to the total dose. A detailed comparison of results using these two standards is presented in Appendix C.

The DCF for air submersion for each radionuclide is calculated by taking the ratio of the unit dose rate, $D_{nuclide}$, from contaminated air in the main or emplacement drift to the unit dose rate from exposure in a semi-infinite slab source. This geometry factor is then used to scale the DCF for air submersion from Table 13.30.1 of Shleien et al. (1998). For radionuclides that do not emit gamma rays, the geometry factor is conservatively assumed to be one. For all other radionuclides in Table 8, the geometry factors range from 0.034 to 0.72 (see Appendix C).

In the previous example, the submersion unit dose rates for Am-241 were derived for the semi-infinite slab geometry and the main drift geometry. The geometry factor for that example would be calculated as follows:

$$\text{Americium-241 geometry factor for main drift submersion} = \frac{4.71\times10^{4}}{5.41\times10^{5}} = 0.087.$$

The main drift submersion DCF for Am-241 is then calculated by multiplying this geometry factor by the air submersion effective dose coefficient, 8.18×10^{-16} Sv/s per Bq/m^3, from Shleien et al. (1998, p. 13-84). A factor of 1.168×10^{23} converts the results to conventional units of mrem/yr per μCi /cm^3 (Eckerman and Ryman 1993, p. 57) as follows:

$$DCF_{\text{Am-241, Main Drift Submersion}} = 0.087\,(8.18\times10^{-16})\,(1.168\times10^{23}) = 8.32\times10^{6}$$

This is the value listed in Table 8. Details of the calculations for all other radionuclides and exposure geometries are included in Appendix C.

The DCFs for surface contamination are calculated in a similar way. In this case, the geometry factor is the ratio of the dose from contaminated drift surfaces to the dose from an infinite plane source. This geometry factor is then used to scale the DCF for ground plane contamination from Table 13.30.3 of Shleien et al. (1998). The geometry factor is conservatively assumed to be two for radionuclides that do not emit gamma rays. For all other radionuclides in Table 8, the geometry factors range from 0.99 to 1.8 (see Appendix C).

Table 8. Main and Emplacement Drift Submersion and Surface Exposure Dose Conversion Factors

	DCF for Air Submersion mrem/yr per μCi/cm^3			DCF for Surface Contamination mrem/yr per μCi/cm^2		
Radionuclide	Semi Inf. Slab[a]	Main Drift[b]	Empl. Drift[b]	Inf. Plane[c]	Main Drift[b]	Empl. Drift[b]
H-3	3.87×10^4	3.87×10^4	3.87×10^4	0	0	0
Co-60	1.47×10^{10}	6.66×10^8	4.75×10^8	2.74×10^6	2.85×10^6	2.66×10^6
Kr-85[d]	1.39×10^7	7.99×10^5	5.65×10^5	3.08×10^3	3.83×10^3	3.61×10^3
Sr-90	8.80×10^5	8.80×10^5	8.80×10^5	3.32×10^2	6.63×10^2	6.63×10^2
Y-90	2.22×10^7	2.22×10^7	2.22×10^7	6.21×10^3	1.24×10^4	1.24×10^4
Ru/Rh-106	1.21×10^9	6.68×10^7	4.74×10^7	2.48×10^5	2.95×10^5	2.77×10^5
Sb-125	2.36×10^9	1.37×10^8	9.73×10^7	4.96×10^5	6.07×10^5	5.71×10^5
I-129	4.44×10^7	3.18×10^7	2.45×10^7	3.01×10^4	5.35×10^4	5.29×10^4
Cs-134	8.84×10^9	4.79×10^8	3.40×10^8	1.78×10^6	2.06×10^6	1.94×10^6
Cs-137	9.04×10^5	9.04×10^5	9.04×10^5	3.33×10^2	6.66×10^2	6.66×10^2
Ba-137m	3.36×10^9	1.84×10^8	1.31×10^8	6.84×10^5	7.98×10^5	7.49×10^5
Eu-154	7.17×10^9	3.63×10^8	2.58×10^8	1.39×10^6	1.56×10^6	1.46×10^6
Eu-155	2.91×10^8	1.95×10^7	1.39×10^7	6.89×10^4	1.03×10^5	9.88×10^4
Am-241	9.55×10^7	8.32×10^6	6.07×10^6	3.21×10^4	4.85×10^4	4.66×10^4

NOTES: [a] Source: Shleien et al. 1998, Table 13.30.1, after conversion to conventional units.

[b] See Appendix C in this report for details of the calculations.

[c] Source: Shleien et al. 1998, Table 13.30.3, after conversion to conventional units.

[d] Kr-85 is a noble gas that is not expected to deposit on surfaces. Non-zero surface contamination DCFs are included here to reflect non-zero values reported for this radionuclide in Shleien et al. (1998).

For each radionuclide, the external gamma dose to a receptor in the middle of an emplacement or main drift is calculated as follows:

$$h_E = (C_a \, DCF_a + C_s \, DCF_s) \, t/8760 \qquad \text{(Eq. 24)}$$

where

h_E = effective dose equivalent (mrem)
C_a = concentration of radionuclide in air (μCi/cm^3)
C_s = concentration of radionuclide on drift surfaces (μCi/cm^2)

DCF_a = dose conversion factor for contaminated air in drift (mrem/yr per $\mu Ci/cm^3$)
DCF_s = dose conversion factor for contamination on drift surface (mrem/yr per $\mu Ci/cm^2$)
t = time spent at receptor location (hr)
8760 = number of hours in one year

If a receptor is in the main drift at an emplacement drift turnout, the dose may be conservatively estimated by multiplying the main drift dose by 1.5. If the receptor is located at the point where the drift diameter changes from main to emplacement drift, the dose may be conservatively estimated by taking the average of the main and emplacement drift doses. These approximations do not take credit for shielding afforded by intervening structural materials or the curvature in the emplacement drift turnout.

The DCFs that are reported for the main drift in Table 8 were independently verified (see Appendix C of this report for details) using the MCNP 4B2 code described in section 5.1. For all of the gamma-emitting radionuclides in Table 8, except I-129, an agreement of better than 20% was achieved, providing reasonable assurance that the calculations have been performed correctly. The uncertainty in the I-129 DCFs results from the very low gamma-ray energies emitted by this radionuclide. However, this radionuclide is not expected to be a significant contributor to the overall dose from air submersion or surface contamination.

6.9 INHALATION DOSE CONVERSION FACTORS AND RESPIRATORY PROTECTION

Releases of gaseous and particulate radionuclides may result in inhalation doses to workers located in the repository drifts. Unlike external gamma DCFs, inhalation DCFs are not geometry-dependent, and no modification of the standard DCFs is needed. For the radionuclides considered in the previous section, Table 9 summarizes the annual limits on intake (ALI), the derived air concentrations (DACs), and the DCFs for inhalation compiled from Tables 1.b and 2.1 of Eckerman et al. (1988). The ALIs are "defined as that activity of a radionuclide which, if inhaled...by Reference Man, will result in a dose equal to the most limiting primary guide for committed dose." (Eckerman et al. 1988, p. 9). The primary guide for most radionuclides is the effective dose equivalent limit of 5 rem/year. The DACs are "defined as that concentration of radionuclide in air which, if breathed by Reference Man for a work-year, would result in the intake of one ALI." (Eckerman et al. 1988, p. 10). The ALIs, DACs, and DCFs tabulated in Eckerman et al. (1988) are consistent with the ALIs and DACs tabulated in 10 CFR 20, Appendix B.

The DAC assumes an inhalation rate of 1.2 m^3/hr. If the concentration in air is known, but the inhalation rate is unknown, the dose to a worker may be calculated for each radionuclide as follows:

$$h_{E,50} = 5000\ (C_a / DAC)\ t/2000 \qquad \text{(Eq. 25)}$$

where

$h_{E,50}$ = 50-year committed effective dose equivalent (mrem)
5000 = occupational dose limit (mrem)

C_a = concentration of radionuclide in air ($\mu Ci/cm^3$)
DAC = derived air concentration ($\mu Ci/cm^3$)
t = time spent inhaling contaminated air (hr)
2000 = hours in a work year

or, if the inhalation rate is assumed to be less than or greater than 1.2 m^3/hr:

$$h_{E,50} = C_a \times IR \times DCF_{inh} \times t \qquad \text{(Eq. 26)}$$

where

IR = inhalation rate (cm^3/hr)
DCF_{inh} = dose conversion factor for inhalation (mrem/μCi)

Table 9. Annual Limits on Intake, Derived Air Concentrations, and Dose Conversion Factors for Inhalation

	ALI[a]	DAC[a]	DCF[b]	
Radionuclide	µCi	µCi/cm³	Sv/Bq	mrem/µCi
H-3	8×10^4	2×10^{-5}	1.73×10^{-11}	6.40×10^{-2}
Co-60	3×10^1	1×10^{-8}	5.91×10^{-8}	2.19×10^2
Kr-85[c]	NA	1×10^{-4}	NA	NA
Sr-90	4	2×10^{-9}	3.51×10^{-7}	1.30×10^3
Y-90	6×10^2	3×10^{-7}	2.28×10^{-9}	8.44
Ru/Rh-106	1×10^1	5×10^{-9}	1.29×10^{-7}	4.77×10^2
Sb-125	5×10^2	2×10^{-7}	3.30×10^{-9}	1.22×10^1
I-129	9	4×10^{-9}	4.69×10^{-8}	1.74×10^2
Cs-134	1×10^2	4×10^{-8}	1.25×10^{-8}	4.63×10^1
Cs-137	2×10^2	6×10^{-8}	8.63×10^{-9}	3.19×10^1
Ba-137m[d]	NA	NA	NA	NA
Eu-154	2×10^1	8×10^{-9}	7.73×10^{-8}	2.86×10^2
Eu-155	9×10^1	4×10^{-8}	1.12×10^{-8}	4.14×10^1
Am-241	6×10^{-3}	3×10^{-12}	1.20×10^{-4}	4.44×10^5

NOTES: [a] Source: Eckerman et al. 1988, Table 1.b.

[b] Source: first column from Eckerman et al. 1988, Table 2.1; second column results from multiplying the first column by 3.7×10^9, which converts first column DCFs to conventional units of mrem/µCi.

[c] Kr-85 is a noble gas; the dose to an individual is from submersion, not inhalation.

[d] Ba-137m is the short-lived decay product of Cs-137; its dose is included in the latter.

NA – Not Applicable

Respiratory protection equipment may be used to protect workers from airborne radionuclides. For the reader's convenience, Appendix D of this report reproduces the equipment-specific protection factors listed in 10 CFR 20, Appendix A, which may be applied to reduce the concentrations of radionuclides in air to which a worker may be exposed. The following formula is used to estimate the concentration of inhaled radionuclides:

$$\begin{pmatrix}\text{Concentration}\\ \text{inhaled}\end{pmatrix} = \frac{\begin{pmatrix}\text{Ambient airborne}\\ \text{concentration}\end{pmatrix}}{\begin{pmatrix}\text{Protection}\\ \text{factor}\end{pmatrix}} \qquad \text{(Eq. 27)}$$

7. CONCLUSIONS

Methods that may be used in contaminant release, transport, and dose analyses for the MGR subsurface facilities are presented in this report. Both hand calculation models and more sophisticated computer codes that may be useful for the analysis of contaminant release and transport are included. The hand calculation models are designed for steady state and one-segment contaminant transport analyses, while the computer codes (TVENT1P and MSPEC codes) may be indicated for more complicated analyses involving repository network(s) and flow transients. A generalized fluid, heat and mass transport computer code (ANSWER code) is also discussed. This code may be desirable if detailed three-dimensional fluid, heat and mass transport analyses within an emplacement drift are required. As indicated in Section 5.3, the TVENT1P, MSPEC, and ANSWER codes have not completed qualification per AP-SI.1Q, but will require such qualification to be completed prior to their use in quality-affecting work.

Contaminant transport mechanisms associated with particle deposition and resuspension are considered. Models that may be used to estimate the potential source terms are included, but it is highly recommended that the reader review and evaluate more current information when this becomes available.

Some limitations exist in the present data for modeling contaminant deposition and resuspension within the emplacement drifts. The temperature of the emplacement drifts, with the waste packages emplaced, may exceed the boiling point of water (Stroupe 2000, Attachment 1, p. 1). At present, little is known about the particle deposition and entrainment behavior under heated conditions. With possible resuspension rates ranging from 0 to about 10^{-5}/sec and resuspension factors from about 10^{-8} to 10^{-2}/m, the amount of deposited contaminant that is entrained into the air can not be realistically estimated. It is recommended that experimental data be developed to determine the behavior of aerosols, similar to that of the CRUD and fuel particles, under the expected high temperature conditions inside the emplacement drifts.

Additional uncertainty is introduced when considering the age of the fuel. Average burnup in recently discharged spent nuclear fuel is higher than in older fuel. The former may have significantly different particulate or gaseous release properties relative to the lower-burnup fuels that are the subject of past analyses. Finally, the fuel properties described in this report are relevant to spent fuel assemblies that has been in storage for a short period relative to the potential pre-closure time in the repository. Release events late in the pre-closure period would affect aged fuel with potentially different, but as yet unquantified, properties.

Geometry factors calculated in the main and emplacement drifts result in air submersion DCFs ranging from 3.4% to 100% of the standard values tabulated for submersion in a semi-infinite cloud. For exposure to contaminated drift surfaces, the calculated DCFs range from 99% to 200% of the standard values tabulated for exposure to an infinite plane source. While most of the dose to unprotected subsurface workers may result from inhalation of airborne radionuclides, the use of respiratory protection equipment could possibly lower the inhalation dose to the point that external exposure is no longer an insignificant portion of the total dose.

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APPENDIX A

DERIVATION OF CONTAMINANT TRANSPORT MODELS

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APPENDIX A - DERIVATION OF CONTAMINANT TRANSPORT MODELS

The contaminant activity or mass concentrations in a segment of a tunnel with radius of R along a one-dimensional direction in x can be calculated by applying the law of conservation of mass to a cylindrical volume element $\pi R^2 \Delta x$ fixed in space, through which the contaminant is flowing (Figure 1).

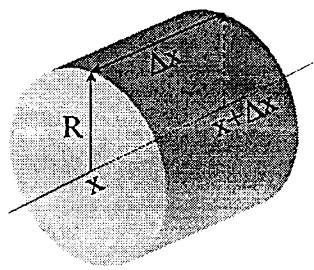

Figure A-1. Cylindrical Volume Element

Within this volume element, the contaminant is released from the wall surface with a contaminant flux rate of F (pCi/m²/s). The various contributions to mass balance are:

Time rate of change of mass of contaminant in volume element	$\frac{\partial C_a}{\partial t} \pi R^2 \Delta x$
Input of contaminant across face at x	$UC_a\big\|_x \pi R^2$
Output of contaminant across face at x + Δx	$UC_a\big\|_{x+\Delta x} \pi R^2$
Rate of contaminant injection from surface source	$2\pi RF\Delta x$
Rate of contaminant depleted from deposition in volume element	$2\pi RV_r C_a \Delta x$

where

C_a = contaminant air concentration (pCi/m³)
F = average contaminant flux (pCi/m²/s)
Δx = a small increment distance in x (m)
R = repository radius (m)
U = cross-section averaged ventilation flow rate (m/s)
$V_r = (V_d - V_s/2)$ = contaminant removal velocity (m/s)
V_d = deposition velocity (m/s)
V_s = settling velocity (m/s)

The mass balance equations after dividing through by $\pi R^2 \Delta x$ and letting the size of the volume element decrease to zero is:

$$\frac{\partial C_a}{\partial t} = -U\frac{\partial C_a}{\partial x} + 2\frac{F}{R} - 2\frac{V_r C_a}{R} \qquad \text{(Eq. A-1)}$$

This is the equation of continuity for contaminant in a segment of the repository. It describes the changes of mass concentration of contaminants with respect to time resulting from ventilation flow velocity of U and removal velocity V_r on to the wall surfaces.

At steady state, $\frac{\partial C_a}{\partial t} = 0$, and Equation A-1 becomes:

$$\frac{U}{2}\frac{dC_a}{dx} = \frac{F}{R} - \frac{V_r}{R}C_a \qquad \text{(Eq. A-2)}$$

The solution for Equation A-2 for the contaminant concentration at x_2 using a boundary condition that the contaminant concentration at x_1 is $C_a(x_1)$ can be written as:

$$C_a(x_2) = C_a(x_1)\,e^{-k(x_2-x_1)} + \frac{F}{V_r}\left(1 - e^{-k(x_2-x_1)}\right) \qquad \text{(Eq. A-3)}$$

where

$k = \frac{2V_r}{UR}$
$C_a(x_2)$ = contaminant air concentration at x_2 (pCi/m^3)
$C_a(x_1)$ = contaminant air concentration at x_1 (pCi/m^3)

For a stationary source, S, located between x_1 and x_2, the contaminant flux, F, may be calculated by the following equation:

$$F = \frac{S}{2\pi R \Delta Xs} \qquad \text{(Eq. A-4)}$$

where

F = average contaminant surface flux (pCi/m^2/s)
ΔXs = size or length of the stationary source (m)
S = contaminant source release rate (pCi/s)
R = repository drift radius (m)

The surface contaminant concentrations from the airborne source are calculated from the calculated airborne concentrations (not including air concentrations resulting from resuspension of previously deposited contaminants). The phenomenon of resuspension is treated neither as a loss nor as a source of surface concentrations (net contribution is zero). Thus, the surface concentration of a contaminant depends directly on the direct deposition rate, which is given by the following relationship:

$$D_d(x) = C_a(x)\, V_d \qquad \text{(Eq. A-5)}$$

where $D_d(x)$ is the contaminant surface deposition rate (pCi/m^2-s).

The contaminant concentration on a surface due to constant deposition at the rate D_d after time interval T_d is obtained from:

$$C_s = D_d\, T_d = C_a(x)\, V_d\, T_d \qquad \text{(Eq. A-6)}$$

where

C_s = contaminant surface concentration at time $t = T_d$ (pCi/m^2).
T_d = time interval over which deposition has occurred (sec)

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APPENDIX B

SCALE V4.3V AND MCNP V4B2LV SAMPLE INPUT FILES

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APPENDIX B - SCALE V4.3V AND MCNP V4B2LV SAMPLE INPUT FILES

Sample SCALE V4.3V Input File SUBM_MD1.IN

```
=NITAWL
0$$  86  E       1$$  F0  A2  11  E      T
2$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
    7014   T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-1
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 1.0E6 F0   T
33** F0    T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-2
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 0 1.0E6 F0   T
33** F0    T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-3
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 2R0 1.0E6 F0   T
```

```
33** F0    T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-4
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 3R0 1.0E6 F0   T
33** F0    T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-5
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 4R0 1.0E6 F0   T
33** F0    T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-6
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 5R0 1.0E6 F0   T
33** F0    T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-7
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
```

```
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 6R0 1.0E6 F0   T
33** F0     T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-8
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 7R0 1.0E6 F0   T
33** F0     T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
=XSDRNPM
AIR SUBMERSION DOSE FACTOR WITHIN MAIN DRIFT - RADIUS 381CM GROUP-9
1$$ 2 2 60 1 0 2 12 12 3 0 100 20 0 0 3
3$$ A2 1 E    5** A3 0.0 E    T
13$$  10R1 2R2
14$$ 1001 8016 14000 20000 11023 12000 13027 16000 19000 26000
     7014 8016
15** 7.724-3 4.411-2 1.591-2 2.917-3 1.047-3 1.514-4 2.387-3 5.739-5
     6.914-4 3.117-4      4.215-5 9.228-6    T
30$$ 50R1 F0
31** 8R0 1.0E6 F0   T
33** F0     T
35** 49I0 9I381.0 431.0
36$$ 50R1 10R2    39$$ 2 1    40$$ F3    T
END
```

Sample MCNP V4B2LV Input File COAIR

```
dose conversion factor for Co-60
c     airborne source (1 microcurie/cc)
c     main drift
c     200m axial height model (100m * 2)
c     drift diameter=7.62 m
c
*******************************************************************
c     main drift
1     1 -0.001225     -1 3 -4
c     surounding host rock
2     2 -2.22         1 -2 3 -4
c     zero importance cell
3     0               2:-3:4

1     cx  381.0
2     cx  411.0
3     px  -1000.0
4     px  10000.0

c     air (0.001225 g/cc)
m1     7014  -0.8
       8016  -0.2
c     dry tuff material (2.22 g/cc)
m2     8016  -0.49863
      11023  -0.02909
      12000  -0.00077
      13027  -0.06513
      14000  -0.36898
      15031  -0.00004
      19000  -0.02641
      20000  -0.00322
      22000  -0.00056
      25055  -0.00035
      26000  -0.00682
mode    p
imp:p   1 0.5 0
esplt:p 0.5 0.25 0.5 0.1
phys:p  3.0
sdef    pos=0 0 0 rad=d1 ext=d2 erg=d3 axs=1 0 0
si1     0 381.0
si2     0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
sp2     0 0.1  0.1  0.1  0.1  0.1  0.1  0.1  0.1  0.1  0.1
sb2     0 0.858 0.088 0.027 0.012 0.006 0.004 0.002 0.001 9.25e-4
6.08e-4
si3     1  1.173216  1.332486
sp3        0.5    0.5
fc5   gamma dose rates--mrem/hr per pho/s*cm2--ANSI 6.1.1-1977
e5    0.045 0.1 0.45 0.70 1.0 1.5 2.0 3.0
f5:p  0.0 0.0 -281.0 0.05
```

```
de5    0.010    0.030    0.050    0.070    0.100    0.150
       0.200    0.250    0.300    0.350    0.400    0.450
       0.500    0.550    0.600    0.650    0.700    0.800
       1.000    1.400    1.800    2.200    2.600    2.800
       3.25     3.75     4.25     4.75     5.0      5.25
       5.75     6.25     6.75     7.5      9.0      11.0
       13.0     15.0
df5    3.96-3   5.82-4   2.90-4   2.58-4   2.83-4   3.79-4
       5.01-4   6.31-4   7.59-4   8.78-4   9.85-4   1.08-3
       1.17-3   1.27-3   1.36-3   1.44-3   1.52-3   1.68-3
       1.98-3   2.51-3   2.99-3   3.42-3   3.82-3   4.01-3
       4.41-3   4.83-3   5.23-3   5.60-3   5.80-3   6.01-3
       6.37-3   6.74-3   7.11-3   7.66-3   8.77-3   1.03-2
       1.18-2   1.33-2
c      multiplier=(1 microCi/cc)(3.7E+4 Bq/microCi)(2 pho/s*Bq)(4.56E+9
cc)
c                 (8760 hr/yr)(2 halves of geometry)= 5.9119E+18
fm5    5.9119E+18
fc15    gamma dose rates--mrem/hr per pho/s*cm2--ANSI 6.1.1-1991(AP-PA)
e15     0.045 0.1 0.45 0.70 1.0 1.5 2.0 3.0
f15:p   0.0 0.0 -281.0 0.05
de15    0.010    0.015    0.020    0.030    0.040    0.050
        0.060    0.080    0.100    0.150    0.200    0.300
        0.400    0.500    0.600    0.800    1.000    1.500
        2.000    3.000    4.000    5.000    6.000    8.000
        10.00    12.00
df15    1.118E-05 3.384E-05 5.846E-05 8.820E-05 1.057E-04
        1.159E-04 1.235E-04 1.431E-04 1.712E-04 2.522E-04
        3.373E-04 5.148E-04 6.876E-04 8.532E-04 1.010E-03
        1.307E-03 1.580E-03 2.167E-03 2.677E-03 3.584E-03
        4.410E-03 5.184E-03 5.922E-03 7.380E-03 8.802E-03
        1.039E-02
c      multiplier=(1 microCi/cc)(3.7E+4 Bq/microCi)(2 pho/s*Bq)(4.56E+9
cc)
c                 (8760 hr/yr)(2 halves of geometry)= 5.9119E+18
fm15   5.9119E+18
fq0    e f
ctme   20.0
```

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APPENDIX C

EXCEL 97 SPREADSHEET FILES USED IN CALCULATING DCFs

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APPENDIX C - EXCEL 97 SPREADSHEET FILES USED IN CALCULATING DCFs

This appendix includes hardcopy versions of the four Excel 97 spreadsheets (workbooks) used in calculating DCFs (pages C-3 through C-52). Each of these four workbooks is subdivided into a number of sheets. To make it easier in identifying the pages that correspond to each workbook, this Appendix is subdivided into 4 subsections, C.1 through C.4. A detailed description of each workbook appears in the introduction to each subsection. Within each subsection, a header is used to identify the workbook (top left-hand corner) and sheet within that workbook (top right-hand corner). Due to formatting limitations in Excel, the headers and footers for pages with landscape orientation appear on the left and right margins of the page, respectively.
Figure C-1 shows the flow of data inputs to, and outputs from, the workbooks (identified by the extension **.xls*). It also includes inputs to, and outputs from, the SCALE V4.3V and MCNP V4B2LV codes (see Appendix B).

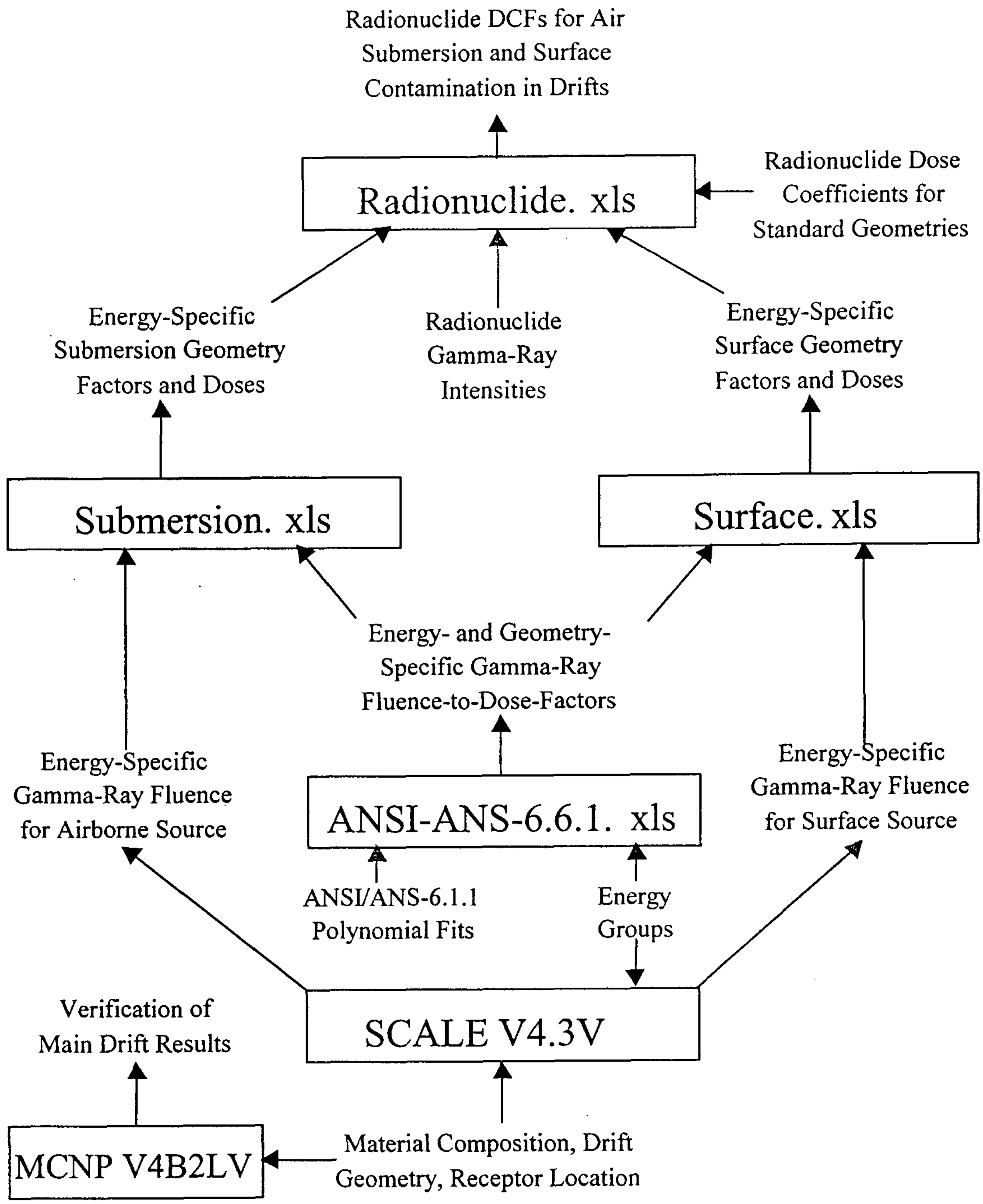


Figure C-1. Flowchart of Codes, Spreadsheets, and Data Used to Derive the DCFs for Air Submersion and Surface Contamination in Repository Drifts

C.1 Radionuclide DCF.xls: Radionuclide Contamination External Dose Factors

1. Purpose

The purpose of this workbook, *Radionclide DCF.xls*, is to derive the main and emplacement drift dose conversion factors (DCFs) for air submersion and surface contamination. These DCFs are tabulated for a set of radionuclides selected for their importance in modeling airborne contamination in the pre-closure repository sub-surface environment. The selected radionuclides are: H-3, Co-60, Kr-85, Sr-90, Y-90, Ru/Rh-106, Sb-125, I-129, Cs-134, Cs-137, Ba-137m, Eu-154, Eu-155, and Am-241. These radionuclides are expected to contribute more than 99.9% of the dose from a contaminant release (CRWMS M&O 1998c).

2. Organization and Function

There are eight sheets (including this Introduction) within this workbook. The right-hand header identifies the name of the sheet. The function and calculations performed by each sheet, as well as any input and output values or links, are summarized in the following sections. The variable names that have been assigned to each sheet are identified. These are used to simplify the calculation formulas used in this workbook. The formulas themselves are described in each sheet. Color coding, shading, and text boxes are used throughout this workbook to report the calculations performed and identify the names and ranges of input and output cells.

2.1 Introduction

This sheet.

2.2 Summary

This sheet summarizes the information contained in the Air Submersion DCF and Drift Surface DCF sheets of this workbook. Refer to those sheets for further information and the calculation of the values in the table. The summary table is formatted for presentation in the main text of this report.

2.3 Gamma Intensities

This sheet tabulates the photon emission intensities for the radionuclides identified in Section 1 above. The first three columns of the table are the gamma-ray energies corresponding to the 18 groups used in the SCALE 4.3 fluence calculations. The source of these values is a link from the *ANSI-ANS-6.1.1.xls* workbook (see C.4). The following columns, headed by the radionuclide names, indicate the total intensity or number (in percent) of gamma- and x-ray (photon) emissions per decay of the radionuclide within each of the 18 energy groups and the total emission intensity. The source of these values is Kocher (1981). The radionuclides that do not emit photons are highlighted, as are the cells containing non-zero gamma-ray intensities.

There are 15 named ranges in this sheet: Nuclide_Names (the row of radionuclide names), and the 14 gamma-ray intensity arrays starting with H_3_GI and ending with Am_241_GI (the first few alphanumeric characters identify the radionuclide, and GI stands for Gamma Intensity). The Nuclide_Names array is used in all of the following sheets, but is transposed from row to column format using the TRANSPOSE function. The GI arrays are used in the Submersion Geometry Factors and Surface Geometry Factors sheets.

2.4 Submersion Geometry Factors

This sheet calculates the radionuclide-specific geometry factors for air submersion taking into account the gamma-ray intensity in each energy group. The radionuclide names are listed in the first column. The following three columns calculate the radionuclide doses for the semi-infinite slab, main drift, and emplacement drift geometries, respectively. These calculation are performed by a matrix multiplication of the radionuclide GI array and the appropriate dose array (Semi_Inf_Slab_Dose, Main_Drift_Dose, and Empl_Drift_Dose, respectively) from the *Submersion DCF.xls* workbook (see C.2). The resulting radionuclide dose arrays are named Semi_Inf_Slab_Dose (used in the Verification Check sheet of this workbook), Subm_Main_Drift_Dose, and Subm_Empl_Drift_Dose, respectively. The final two columns are the calculated radionuclide geometry factors for the main and emplacement drifts. They are calculated by dividing the Subm_Main_Drift_Dose and Subm_Empl_Drift_Dose arrays, respectively, by the Semi_Inf_Slab_Dose array. For radionuclides that do not emit gamma rays, the geometry factor is set to one. The two geometry factor columns are named Subm_Main_Drift_GF and Subm_Empl_Drift_GF, respectively. These two arrays are used in the Air Submersion DCF sheet of this worbook.

2.5 Surface Geometry Factors

This sheet calculates the radionuclide-specific geometry factors for surface contamination taking into account the gamma-ray intensity in each energy group. The radionuclide names are listed in the first column. The following three columns calculate the radionuclide doses for the infinite plane, main drift, and emplacement drift geometries, respectively. These calculation are performed by a matrix multiplication of the radionuclide GI array and the appropriate dose array (Inf_Plane_Dose, Main_Drift_Dose, and Empl_Drift_Dose, respectively) from the *Surface DCF.xls* workbook (see C.3). The resulting radionuclide dose arrays are named Inf_Plane_Dose (used in the Verification Check sheet of this workbook), Surf_Main_Drift_Dose, and Surf_Empl_Drift_Dose, respectively. The final two columns are the calculated radionuclide geometry factors for the main and emplacement drifts. They are calculated by dividing the Surf_Main_Drift_Dose and Surf_Empl_Drift_Dose arrays, respectively, by the Inf_Plane_Dose array. For radionuclides that do not emit gamma rays, the geometry factor is set to two. The two geometry factor columns are named Surf_Main_Drift_GF and Surf_Empl_Drift_GF, respectively. These two arrays are used in the Drift Surface DCF sheet of this workbook.

2.6 Air Submersion DCF

This sheet calculates the radionuclide-specific dose conversion factor for air submersion in the main and emplacement drifts. The radionuclide names are listed in the first column. The second column reproduces the effective dose equivalent coefficients for air submersion from Federal Guidance Report (FGR) 12 as they appear in Table 13.30.1 of Shleien et al. (1998). This input array is named FGR12_Subm_DCF. The third column converts the values in FGR12_Subm_DCF to conventional units; the resulting array is named Semi_Inf_Slab_DCF and is used in the QA Check sheet of this workbook. The final two columns are the ground exposure dose factors calculated for the main and emplacement drift geometries by multiplying Semi_Inf_Slab_DCF by Subm_Main_Drift_GF and Subm_Empl_Drift_GF, respectively. The resulting arrays are named Subm_Main_Drift_DCF and Subm_Empl_Drift_DCF, respectively.

2.7 Drift Surface DCF

This sheet calculates the radionuclide-specific dose conversion factor for surface contamination in the main and emplacement drifts. The radionuclide names are listed in the first column. The second column reproduces the effective dose equivalent coefficients for air submersion as they appear in Table 13.30.3 of Shleien et al. (1998). This input array is named FGR12_Ground_DCF. The third column converts the values in FGR12_Ground_DCF to conventional units; the resulting array is named Inf_Plane_DCF and is used in the Verification Check sheet of this workbook. The final two columns are the surface exposure dose factors calculated for the main and emplacement drift geometries by multiplying Inf_Plane_DCF by Surf_Main_Drift_GF and Surf_Empl_Drift_GF, respectively. The resulting arrays are named Surf_Main_Drift_DCF and Surf_Empl_Drift_DCF, respectively.

2.8 Verification Check

This sheet includes six tables. The first two calculate the difference in dose factors calculated using SCALE 4.3 and ANSI/ANS-6.1.1-1991 versus FGR 12 dose factors presented in Tables 13.30.1 and 13.30.3 of Shleien et al. (1998), respectively. The next two tables calculate the geometry factors between FGR 12 dose factors and main drift dose factors calculated using ANSI/ANS-6.1.1-1977 flux-to-dose factors. The final two tables compare the results for the main drift using MCNP 4B2.

3.0 Results and Conclusions

In the Verification Check sheet of this workbook, for most of the radionuclides that are not NA, the difference between the FGR 12 dose factors and the calculated SCALE 4.3 - ANSI/ANS-6.1.1-1991 dose factors is less than 10%. Where the differences are greater than 10%, these can be attributed to the greater discrepancies in the fluence-to-dose factors for low-energy gamma emitters. These discrepancies are a secondary effect: the actual deviations when using the Geometry Factors will be much smaller, since the latter are applied directly to the FGR 12 dose coefficients to obtain the main and emplacement drift DCFs for air sumbersion and surface exposure. For low-energy gamma-emitters such as I-129, the geometry factors for the main drift calculated from SCALE 4.3 - ANSI/ANS-6.1.1-1977 are unrealistically high due to the large differences in fluence-to-dose factors between the 1991 and 1977 standards at low gamma-ray energies. Good agreement was found with the results calculated using the MCNP 4B2 code for the main drift, providing independent verification of the results obtained using SCALE 4.3.

4. Workbook Links

The following named ranges from *ANSI-ANS-6.1.1.xls* are input links for this workbook: Group_Number, Upper_Energy, Mean_Energy.

The following named ranges from *Surface DCF.xls* are input links for this workbook: Inf_Plane_Dose, Main_Drift_Dose, Main_Drift_Dose_77, and Empl_Drift_Dose.

The following named ranges from *Submersion DCF.xls* are input links for this workbook: Semi_Inf_Slab_Dose, Main_Drift_Dose, Main_Drift_Dose_77, and Empl_Drift_Dose.

This workbook does not have output links to any other workbook, but the summary results are used in the main text of this report.

Author: E. R. Faillace - last modified 8/22/2000

Summary Table for Presentation in Table 8 in Main Body of Text

	DCF for Air Submersion			DCF for Surface Contamination		
	Semi Inf. Slab	Main Drift	Empl. Drift	Inf. Plane	Main Drift	Empl. Drift
Radionuclide	mrem/yr per $\mu Ci/cm^3$			mrem/yr per $\mu Ci/cm^2$		
H-3	3.87E+04	3.87E+04	3.87E+04	0.00E+00	0.00E+00	0.00E+00
Co-60	1.47E+10	6.66E+08	4.75E+08	2.74E+06	2.85E+06	2.66E+06
Kr-85	1.39E+07	7.99E+05	5.65E+05	3.08E+03	3.83E+03	3.61E+03
Sr-90	8.80E+05	8.80E+05	8.80E+05	3.32E+02	6.63E+02	6.63E+02
Y-90	2.22E+07	2.22E+07	2.22E+07	6.21E+03	1.24E+04	1.24E+04
Ru/Rh-106	1.21E+09	6.68E+07	4.74E+07	2.48E+05	2.95E+05	2.77E+05
Sb-125	2.36E+09	1.37E+08	9.73E+07	4.96E+05	6.07E+05	5.71E+05
I-129	4.44E+07	3.18E+07	2.45E+07	3.01E+04	5.35E+04	5.29E+04
Cs-134	8.84E+09	4.79E+08	3.40E+08	1.78E+06	2.06E+06	1.94E+06
Cs-137	9.04E+05	9.04E+05	9.04E+05	3.33E+02	6.66E+02	6.66E+02
Ba-137m	3.36E+09	1.84E+08	1.31E+08	6.84E+05	7.98E+05	7.49E+05
Eu-154	7.17E+09	3.63E+08	2.58E+08	1.39E+06	1.56E+06	1.46E+06
Eu-155	2.91E+08	1.95E+07	1.39E+07	6.89E+04	1.03E+05	9.88E+04
Am-241	9.55E+07	8.32E+06	6.07E+06	3.21E+04	4.85E+04	4.66E+04

Photon Intensities for Important Radionuclides as a Function of Gamma-Ray Energy Group

Energy Group	Gamma-Ray Energy (E) Upper (eV)	Gamma-Ray Energy (E) Mean (MeV)	Photon Intensities (%) H-3	Co-60	Kr-85	Sr-90	Y-90	Ru/Rh-106	Sb-125	I-129	Cs-134	Cs-137	Ba-137m	Eu-154	Eu-155	Am-241
1	1.00E+07	9.00E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	8.00E+06	7.25E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	6.50E+06	5.75E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	5.00E+06	4.50E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	4.00E+06	3.50E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	3.00E+06	2.75E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	2.50E+06	2.25E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	2.00E+06	1.83E+00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1.66E+06	1.50E+00	0	100.0%	0	0	0	0.2%	0	0	3.0%	0	0	3.5%	0	0
10	1.33E+06	1.17E+00	0	100.0%	0	0	0	2.1%	0	0	2.8%	0	0	55.2%	0	0
11	1.00E+06	9.00E-01	0	0	0	0	0	0.4%	0	0	8.7%	0	0	24.3%	0	0
12	8.00E+05	7.00E-01	0	0	0	0	0	10.5%	36.0%	0	183.0%	0	90.0%	26.3%	0	0
13	6.00E+05	5.00E-01	0	0	0.4%	0	0	20.6%	40.2%	0	25.3%	0	0	6.9%	0	0
14	4.00E+05	3.50E-01	0	0	0	0	0	0	1.9%	0	0	0	0	0	0	0
15	3.00E+05	2.50E-01	0	0	0	0	0	0	0.7%	0	0	0	0	6.6%	0	0
16	2.00E+05	1.50E-01	0	0	0	0	0	0	7.3%	0	0	0	0	40.7%	20.7%	0
17	1.00E+05	7.50E-02	0	0	0	0	0	0	0	0	0	0	0	0	32.2%	35.9%
18	5.00E+04	3.00E-02	0	0	0	0	0	0	54.1%	85.9%	0.8%	0	8.3%	33.2%	32.4%	45.5%
	1.00E+04	**TOTAL**	0	200.0%	0.4%	0	0	33.8%	140.1%	85.9%	223.6%	0	98.3%	196.7%	85.3%	81.4%

1 eV = 10^{-6} MeV

These radionuclides do not emit gamma rays.

Ru-106 is a pure beta emitter that decays to the short-lived gamma emitter Rh-106.

These photon intensities are obtained from Kocher (1981). The percentages for multiple gamma rays and x-rays falling in one energy group are obtained by summing the percentage intensity from Kocher (1981) for each gamma that falls in that group. The total percentage may exceed 100 due to multiple gammas emitted per decay. For example, the Cs-134 spectrum includes 11 gamma rays. Two of these are emitted at 605 KeV with 97.6% intensity and 796 KeV with 85.4% intensity for a total of 183% gamma-rays emitted in Energy Group 12 (0.6-0.8 MeV). The total intensity of all gamma- and x-rays emitted from Cs-134 is 223.6%. Weak gamma rays are omitted from the above sums due to their low intensity as indicated in Kocher (1981). Due to space restrictions, the intensities are shown as rounded to 1 decimal place, but the underlying values used in the calculations are carried to the same precision as the source.

Air Submersion Dose Summary and Geometry Factors

Radionuclide	Semi Inf. Slab Dose (mrem/hr per MBq/cm^3)	Main Drift Dose (mrem/hr per MBq/cm^3)	Empl. Drift Dose (mrem/hr per MBq/cm^3)	Main Drift Geometry Factor	Empl. Drift Geometry Factor
H-3	0.00E+00	0.00E+00	0.00E+00	1.000	1.000
Co-60	4.76E+07	2.15E+06	1.54E+06	0.045	0.032
Kr-85	3.91E+04	2.25E+03	1.59E+03	0.057	0.041
Sr-90	0.00E+00	0.00E+00	0.00E+00	1.000	1.000
Y-90	0.00E+00	0.00E+00	0.00E+00	1.000	1.000
Ru/Rh-106	3.71E+06	2.04E+05	1.45E+05	0.055	0.039
Sb-125	8.50E+06	4.93E+05	3.51E+05	0.058	0.041
I-129	4.21E+04	3.02E+04	2.32E+04	0.715	0.551
Cs-134	2.77E+07	1.50E+06	1.07E+06	0.054	0.038
Cs-137	0.00E+00	0.00E+00	0.00E+00	1.000	1.000
Ba-137m	1.12E+07	6.12E+05	4.34E+05	0.055	0.039
Eu-154	2.18E+07	1.10E+06	7.85E+05	0.051	0.036
Eu-155	1.16E+06	7.77E+04	5.54E+04	0.067	0.048
Am-241	5.41E+05	4.71E+04	3.44E+04	0.087	0.064

The underlying formulas are:

Semi Inf. Slab Dose =MMULT(TRANSPOSE(Co_60_GI),'Submersion DCF.xls'!Semi_Inf_Slab_Dose)

Main Drift Dose =MMULT(TRANSPOSE(Co_60_GI),'Submersion DCF.xls'!Main_Drift_Dose)

Empl. Drift Dose =MMULT(TRANSPOSE(Co_60_GI),'Submersion DCF.xls'!Empl_Drift_Dose)

These formulas perform a matrix multiplication between the Co-60 gamma-ray intensities array from the Gamma Intensities sheet and the 18-Energy-Group array for either the Semi Inf. Slab Dose, Main Drift Dose or Empl. Drift Dose, respectively, in the **Fluence-to-Dose** sheet of *Submersion DCF.xls*. The result is the radionuclide-specific dose rate for each geometry condition. See Excel Help for more information on the MMULT function.

For other rows, the name of the applicable radionuclide gamma intensity array is substituted for Co_60_GI. For radionuclides that do not emit gamma rays, the result will be zero.

The resulting columns are named: Semi_Inf_Slab_Dose, Subm_Main_Drift_Dose, and Subm_Empl_Drift_Dose, respectively.

The underlying formulas are:

Main Drift Geom. Factor=IF(Semi_Inf_Slab_Dose=0,1, Subm_Main_Drift_Dose/Semi_Inf_Slab_Dose)

Empl. Drift Geom. Factor=IF(Semi_Inf_Slab_Dose=0,1, Subm_Empl_Drift_Dose/Semi_Inf_Slab_Dose)

These formulas calculate the ratio (Geometry Factor) of the dose in the main or emplacement drifts, respectively, to the dose in the semi infinite slab for each radionuclide. If the content of a cell in the Semi_Inf_Slab_Dose column is 0, the IF function prevents a divide by zero error and sets the Geometry Factor for that radionuclide to 1.

The resulting columns are named: Subm_Main_Drift_GF and Subm_Empl_Drift_GF, respectively.

Surface Contamination Dose Summary and Geometry Factors

Radionuclide	Inf. Plane Dose	Main Drift Dose	Empl. Drift Dose	Main Drift Geometry Factor	Empl. Drift Geometry Factor
	mrem/hr per MBq/cm^2				
H-3	0.00E+00	0.00E+00	0.00E+00	2.000	2.000
Co-60	8.77E+03	9.09E+03	8.49E+03	1.037	0.968
Kr-85	8.01E+00	9.95E+00	9.37E+00	1.243	1.170
Sr-90	0.00E+00	0.00E+00	0.00E+00	2.000	2.000
Y-90	0.00E+00	0.00E+00	0.00E+00	2.000	2.000
Ru/Rh-106	7.50E+02	8.92E+02	8.38E+02	1.190	1.118
Sb-125	1.76E+03	2.15E+03	2.03E+03	1.222	1.151
I-129	5.92E+01	1.05E+02	1.04E+02	1.775	1.754
Cs-134	5.62E+03	6.54E+03	6.14E+03	1.163	1.091
Cs-137	0.00E+00	0.00E+00	0.00E+00	2.000	2.000
Ba-137m	2.28E+03	2.66E+03	2.50E+03	1.166	1.095
Eu-154	4.23E+03	4.75E+03	4.45E+03	1.123	1.054
Eu-155	2.30E+02	3.45E+02	3.29E+02	1.501	1.433
Am-241	1.30E+02	1.96E+02	1.88E+02	1.511	1.450

The underlying formulas are:

Infinite Plane Dose =MMULT(TRANSPOSE(Co_60_GI),'Surface DCF.xls'!Inf_Plane_Dose)

Main Drift Dose =MMULT(TRANSPOSE(Co_60_GI),'Surface DCF.xls'!Main_Drift_Dose)

Empl. Drift Dose =MMULT(TRANSPOSE(Co_60_GI),'Surface DCF.xls'!Empl_Drift_Dose)

These formulas perform a matrix multiplication between the Co-60 gamma-ray intensities array from the Gamma Intensities sheet and the 18-Energy-Group array for either the Inf. Plane Dose, Main Drift Dose or Empl. Drift Dose, respectively, in the **Fluence-to-Dose** sheet of *Surface DCF.xls*. The result is the radionuclide-specific dose rate for each geometry condition. See Excel Help for more information on the MMULT function.

For other rows, the name of the applicable radionuclide gamma intensity array is substituted for Co_60_GI. For radionuclides that do not emit gamma-rays, the result will be zero.

The resulting columns are named: Inf_Plane_Dose, Surf_Main_Drift_Dose, and Surf_Empl_Drift_Dose, respectively.

The underlying formulas are:

Main Drift Geometry Factor=IF(Inf_Plane_Dose=0,2, Surf_Main_Drift_Dose/Inf_Plane_Dose)

Empl. Drift Geometry Factor=IF(Inf_Plane_Dose=0,2, Surf_Empl_Drift_Dose/Inf_Plane_Dose)

These formulas calculate the ratio (Geometry Factor) of the dose in the main or emplacement drifts, respectively, to the dose from the infinite plane source for each radionuclide. If the content of a cell in the Inf_Plane_Dose column is 0, the IF function prevents a divide by zero error and conservatively sets the Geometry Factor for that radionuclide to 2.

The resulting columns are named: Surf_Main_Drift_GF and Surf_Empl_Drift_GF, respectively.

Radionuclide Dose Conversion Factors for Air Submersion

Radionuclide	FGR12 Table III.1 Air Submersion Eff. Dose Coeff. Sv/s per Bq/m^3	Dose Conversion Factor for Semi Inf. Slab mrem/yr per µCi/cm^3	Main Drift	Empl. Drift
H-3	3.31E-19	3.87E+04	3.87E+04	3.87E+04
Co-60	1.26E-13	1.47E+10	6.66E+08	4.75E+08
Kr-85	1.19E-16	1.39E+07	7.99E+05	5.65E+05
Sr-90	7.53E-18	8.80E+05	8.80E+05	8.80E+05
Y-90	1.90E-16	2.22E+07	2.22E+07	2.22E+07
Ru/Rh-106	1.04E-14	1.21E+09	6.68E+07	4.74E+07
Sb-125	2.02E-14	2.36E+09	1.37E+08	9.73E+07
I-129	3.80E-16	4.44E+07	3.18E+07	2.45E+07
Cs-134	7.57E-14	8.84E+09	4.79E+08	3.40E+08
Cs-137	7.74E-18	9.04E+05	9.04E+05	9.04E+05
Ba-137m	2.88E-14	3.36E+09	1.84E+08	1.31E+08
Eu-154	6.14E-14	7.17E+09	3.63E+08	2.58E+08
Eu-155	2.49E-15	2.91E+08	1.95E+07	1.39E+07
Am-241	8.18E-16	9.55E+07	8.32E+06	6.07E+06

Multiply **Sv/s per Bq/m^3** by 1.168 x 10^{23} to get **mrem/yr per µCi/cm^3**

The first column reproduces the effective dose equivalent coefficients for air submersion as tbey appear in Table 13.30.1 of Shleien et al. (1998). This column is named FGR12_Subm_DCF.

The second column converts these values to conventional units by using the formula, shown in the above box, from Table III.1 of Eckerman and Ryman (1993):

=FGR12_Subm_DCF*1.168E+23

This column is named Semi_Inf_Slab_DCF.

The underlying formulas for these two columns are:

Main Drift Dose Conversion Factor=Semi_Inf_Slab_DCF*Subm_Main_Drift_GF

Empl. Drift Dose Conversion Factor=Semi_Inf_Slab_DCF*Subm_Empl_Drift_GF

These two columns are named Subm_Main_Drift_DCF and Subm_Empl_Drift_DCF, respectively.

Radionuclide Dose Conversion Factors for Surface Contamination

Radionuclide	FGR12 Table III.3 Ground Surface Eff. Dose Coeff. Sv/s per Bq/m^2	Dose Conversion Factor for Inf. Plane mrem/yr per µCi/cm^2	Main Drift mrem/yr per µCi/cm^2	Empl. Drift mrem/yr per µCi/cm^2
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-60	2.35E-15	2.74E+06	2.85E+06	2.66E+06
Kr-85	2.64E-18	3.08E+03	3.83E+03	3.61E+03
Sr-90	2.84E-19	3.32E+02	6.63E+02	6.63E+02
Y-90	5.32E-18	6.21E+03	1.24E+04	1.24E+04
Ru/Rh-106	2.12E-16	2.48E+05	2.95E+05	2.77E+05
Sb-125	4.25E-16	4.96E+05	6.07E+05	5.71E+05
I-129	2.58E-17	3.01E+04	5.35E+04	5.29E+04
Cs-134	1.52E-15	1.78E+06	2.06E+06	1.94E+06
Cs-137	2.85E-19	3.33E+02	6.66E+02	6.66E+02
Ba-137m	5.86E-16	6.84E+05	7.98E+05	7.49E+05
Eu-154	1.19E-15	1.39E+06	1.56E+06	1.46E+06
Eu-155	5.90E-17	6.89E+04	1.03E+05	9.88E+04
Am-241	2.75E-17	3.21E+04	4.85E+04	4.66E+04

Multiply **Sv/s per Bq/m^2** by 1.168 x 10^{21} to get **mrem/yr per µCi/cm^2**

The first column reproduces the effective dose equivalent coefficients for exposure to contaminated ground surface as tbey appear in Table 13.30.3 of Shleien et al. (1998). This column is named FGR12_Ground_DCF.

The second column converts these values to conventional units by using the formula

=FGR12_Ground_DCF*1.168E+23

This column is named Inf_Plane_DCF.

The underlying formulas for these two columns are:

Main Drift Dose Conversion Factor=Inf_Plane_DCF*Surf_Main_Drift_GF

Empl. Drift Dose Conversion Factor=Inf_Plane_DCF*Surf_Empl_Drift_GF

These two columns are named Surf_Main_Drift_DCF and Surf_Empl_Drift_DCF, respectively.

Comparison of FGR 12 Effective Dose Equivalent Coefficients with Calculated DCFs Using 1991 Fluence-to-Dose Factors

Air Submersion - Semi-Infinite Slab

Radionuclide	FGR 12 EDE Coeff. mrem/yr per µCi/cm^3	SCALE 4.3 Fluence ISO Fluence-to-Dose mrem/hr per MBq/cm^3	mrem/yr per µCi/cm^3	Difference: (Col. D-B)/ Col. D
H-3	3.87E+04	0.00E+00	0.00E+00	NA
Co-60	1.47E+10	4.76E+07	1.54E+10	4.7%
Kr-85	1.39E+07	3.91E+04	1.27E+07	-9.6%
Sr-90	8.80E+05	0.00E+00	0.00E+00	NA
Y-90	2.22E+07	0.00E+00	0.00E+00	NA
Ru/Rh-106	1.21E+09	3.71E+06	1.20E+09	-1.0%
Sb-125	2.36E+09	8.50E+06	2.76E+09	14.4%
I-129	4.44E+07	4.21E+04	1.37E+07	-224.7%
Cs-134	8.84E+09	2.77E+07	9.00E+09	1.7%
Cs-137	9.04E+05	0.00E+00	0.00E+00	NA
Ba-137m	3.36E+09	1.12E+07	3.62E+09	7.0%
Eu-154	7.17E+09	2.18E+07	7.08E+09	-1.4%
Eu-155	2.91E+08	1.16E+06	3.76E+08	22.8%
Am-241	9.55E+07	5.41E+05	1.75E+08	45.5%

Contaminated Surface - Infinite Plane

Radionuclide	FGR 12 EDE Coeff. mrem/yr per µCi/cm^2	SCALE 4.3 Fluence ROT Fluence-to-Dose mrem/hr per MBq/cm^2	mrem/yr per µCi/cm^2	Difference: (Col. J-H)/ Col. J
H-3	0.00E+00	0.00E+00	0.00E+00	NA
Co-60	2.74E+06	8.77E+03	2.84E+06	3.5%
Kr-85	3.08E+03	8.01E+00	2.60E+03	-18.8%
Sr-90	3.32E+02	0.00E+00	0.00E+00	NA
Y-90	6.21E+03	0.00E+00	0.00E+00	NA
Ru/Rh-106	2.48E+05	7.50E+02	2.43E+05	-1.8%
Sb-125	4.96E+05	1.76E+03	5.71E+05	13.1%
I-129	3.01E+04	5.92E+01	1.92E+04	-56.9%
Cs-134	1.78E+06	5.62E+03	1.82E+06	2.7%
Cs-137	3.33E+02	0.00E+00	0.00E+00	NA
Ba-137m	6.84E+05	2.28E+03	7.39E+05	7.4%
Eu-154	1.39E+06	4.23E+03	1.37E+06	-1.4%
Eu-155	6.89E+04	2.30E+02	7.45E+04	7.6%
Am-241	3.21E+04	1.30E+02	4.21E+04	23.7%

The two tables above present a comparison of dose factors calculated using SCALE 4.3 and ANSI/ANS-6.1.1-1991, *Neutron and Gamma-Ray Fluence-to-Dose Factors*, versus those presented in Tables 13.30.1 and 13.30.3 of Shleien et al. (1998). The first column in each table lists the radionuclides for which dose factors are tabulated in this workbook. The second column in each table lists the FGR 12 effective dose equivalent coefficients in conventional units (ranges named Semi_Inf_Slab_DCF and Inf_Plane_DCF, respectively). The third column presents the DCFs calculated using SCALE 4.3 and ANSI/ANS-6.1.1 (ranges named Semi_Inf_Slab_Dose and Inf_Plane_Dose, respectively). The fourth columns are the values from the third column converted to the units of the second column. The conversion factor in both submersion and ground exposure tables is 324.342 hr/yr per µCi/MBq (8766 hr/yr and 27.027 µCi/MBq). The final column is the percent difference between the values in the second and fourth columns. If one of these values is zero, the difference is not computed and an NA appears for that radionuclide.

For most of the radionuclides that are not NA, the difference is less than 10%. Where the differences are greater than 10%, these can be attributed to the greater discrepancies in the fluence-to-dose factors for low-energy gamma emitters. The actual differences when using the Geometry Factors will be much smaller, since the latter are applied directly to the FGR 12 dose coefficients.

Comparison of FGR 12 Effective Dose Equivalent Coefficients with Calculated DCFs Using 1977 Fluence-to-Dose Factors

Air Submersion - Main Drift

Radionuclide	FGR 12 EDE Coeff. mrem/yr per µCi/cm^3	SCALE 4.3 Fluence 1977 Fluence-to-Dose mrem/hr per MBq/cm^3	SCALE 4.3 Fluence 1977 Fluence-to-Dose mrem/yr per µCi/cm^3	Geometry Factor
H-3	3.87E+04	0.00E+00	0.00E+00	NA
Co-60	1.47E+10	2.71E+06	8.77E+08	0.060
Kr-85	1.39E+07	3.14E+03	1.02E+06	0.073
Sr-90	8.80E+05	0.00E+00	0.00E+00	NA
Y-90	2.22E+07	0.00E+00	0.00E+00	NA
Ru/Rh-106	1.21E+09	2.78E+05	9.02E+07	0.074
Sb-125	2.36E+09	7.80E+05	2.53E+08	0.107
I-129	4.44E+07	1.99E+05	6.45E+07	1.454
Cs-134	8.84E+09	2.03E+06	6.59E+08	0.074
Cs-137	9.04E+05	0.00E+00	0.00E+00	NA
Ba-137m	3.36E+09	8.42E+05	2.73E+08	0.081
Eu-154	7.17E+09	1.52E+06	4.92E+08	0.069
Eu-155	2.91E+08	1.88E+05	6.10E+07	0.210
Am-241	9.55E+07	1.64E+05	5.32E+07	0.556

Contaminated Surface - Main Drift

Radionuclide	FGR 12 EDE Coeff. mrem/yr per µCi/cm^2	SCALE 4.3 Fluence 1977 Fluence-to-Dose mrem/hr per MBq/cm^2	SCALE 4.3 Fluence 1977 Fluence-to-Dose mrem/yr per µCi/cm^2	Geometry Factor
H-3	0.00E+00	0.00E+00	0.00E+00	NA
Co-60	2.74E+06	1.16E+04	3.75E+06	1.367
Kr-85	3.08E+03	1.40E+01	4.55E+03	1.477
Sr-90	3.32E+02	0.00E+00	0.00E+00	NA
Y-90	6.21E+03	0.00E+00	0.00E+00	NA
Ru/Rh-106	2.48E+05	1.23E+03	4.00E+05	1.615
Sb-125	4.96E+05	3.35E+03	1.09E+06	2.188
I-129	3.01E+04	6.94E+02	2.25E+05	7.468
Cs-134	1.78E+06	8.94E+03	2.90E+06	1.633
Cs-137	3.33E+02	0.00E+00	0.00E+00	NA
Ba-137m	6.84E+05	3.69E+03	1.20E+06	1.749
Eu-154	1.39E+06	6.57E+03	2.13E+06	1.533
Eu-155	6.89E+04	7.84E+02	2.54E+05	3.691
Am-241	3.21E+04	6.33E+02	2.05E+05	6.388

The two tables above present a comparison of dose factors calculated for the main drift geometry using SCALE 4.3 and ANSI/ANS-6.1.1-1977, *Neutron and Gamma-Ray Flux-to-Dose Factors*, versus those presented in Tables 13.30.1 and 13.30.3 of Shleien et al. (1998) for infinite geometries. The first two columns in each table are the same as in the previous tables. The third column presents the DCFs calculated using the GIs from the **Gamma Intensity** sheet of this workbook and the dose factors caculated using SCALE 4.3 and ANSI/ANS-6.1.1-1977 from the **1991 vs 1977 Standard** sheets of the *Submersion DCF.xls* and *Surface DCF.xls* workbooks. The fourth column in each table convert the values from the third column into the units of the second column. The conversion factor in both submersion and ground exposure tables is 324.342 hr/yr per µCi/MBq (8766 hr/yr and 27.027 µCi/MBq). The final column in each table is the geometry factor between the values in the second and fourth columns. If one of these values is zero, the geometry factor is not computed and an NA appears for that radionuclide.

In the air submersion table, the geometry factor for most radionuclides is either calculated as NA or is less than 1. However, for I-129, this value is greater than 1, which is not realistic since it indicates that calculated doses would exceed the value for submersion in a semi-infinite slab. In the case of the contaminated drift surface, any geometry factor greater than 2 is not realistic relative to exposure from an infinite contaminated plane source.

Comparison of SCALE 4.3/1991 Standard with MCNP 4B2/1977-1991 Standard

Air Submersion - Main Drift

Radionuclide	SCALE 4.3 AP-PA (mrem/yr per μCi/cm^3)	MCNP 4B2 1977 (mrem/yr per μCi/cm^3)	MCNP 4B2 AP-PA (mrem/yr per μCi/cm^3)	Difference: (Col. D-B)/ Col. D
H-3	3.87E+04	NA	NA	NA
Co-60	6.66E+08	8.61E+08	6.79E+08	1.9%
Kr-85	7.99E+05	1.07E+06	7.57E+05	-5.6%
Sr-90	8.80E+05	NA	NA	NA
Y-90	2.22E+07	NA	NA	NA
Ru/Rh-106	6.68E+07	NA	NA	NA
Sb-125	1.37E+08	2.53E+08	1.49E+08	8.1%
I-129	3.18E+07	7.45E+07	1.17E+07	-171.4%
Cs-134	4.79E+08	6.68E+08	4.92E+08	2.6%
Cs-137	9.04E+05	NA	NA	NA
Ba-137m	1.84E+08	2.68E+08	1.93E+08	4.4%
Eu-154	3.63E+08	4.96E+08	3.65E+08	0.6%
Eu-155	1.95E+07	NA	NA	NA
Am-241	8.32E+06	1.13E+08	1.04E+07	20.0%

Contaminated Surface - Main Drift

Radionuclide	SCALE 4.3 AP-PA (mrem/yr per μCi/cm^3)	MCNP 4B2 1977 (mrem/yr per μCi/cm^3)	MCNP 4B2 AP-PA (mrem/yr per μCi/cm^3)	Difference: (Col. J-H)/ Col. J
H-3	0.00E+00	NA	NA	NA
Co-60	2.85E+06	3.61E+06	2.81E+06	-1.3%
Kr-85	3.83E+03	4.68E+03	3.27E+03	-17.2%
Sr-90	6.63E+02	NA	NA	NA
Y-90	1.24E+04	NA	NA	NA
Ru/Rh-106	2.95E+05	NA	NA	NA
Sb-125	6.07E+05	1.07E+06	6.36E+05	4.6%
I-129	5.35E+04	2.71E+05	4.27E+04	-25.3%
Cs-134	2.06E+06	2.88E+06	2.09E+06	1.2%
Cs-137	6.66E+02	NA	NA	NA
Ba-137m	7.98E+05	1.16E+06	8.25E+05	3.2%
Eu-154	1.56E+06	2.10E+06	1.53E+06	-2.0%
Eu-155	1.03E+05	NA	NA	NA
Am-241	4.85E+04	3.74E+05	4.21E+04	-15.3%

The two tables above present a comparison of dose factors calculated for the main drift geometry using SCALE 4.3 and ANSI/ANS-6.1.1-1991, versus those calculated by MCNP 4B2 and both 1977 and 1991 Standards. The second column in each table are the DCFs calculated for the main drift in the **Air Submersion DCF** and **Drift Surface DCF** sheets, respectively. The third and fourth columns present the DCFs calculated by MCNP 4B2 using the 1991 standard's average AP-PA geometry fluence-to-dose factors and the 1977 standard's fluence-to-dose factors, respectively, for either air submersion or surface main drift geometries. The final column in each table is the difference between the SCALE and MCNP (1991 standard) DCFs, i.e., the values in the second and fourth columns. An NA appears for those radionuclides not included in the MCNP runs.

In the air submersion table, the difference for most radionuclides is less than 10%. However, for I-129, MCNP calculates a value that is almost thee time lower. In the ground surface table, the difference for all radionuclides is less than 20%, again with the exception of I-129, where the MCNP results are again lower, but only by 25%. The reasons for the larger discrepancies in the I-129 values can be attributed to the very low energy gamma ray emission from this radionuclide (in the last energy group, where no downscattering is considered). The fact that such good agreement is achieved for most radionuclides using two independent methods provides assurance that the results have been obtained correctly and that the computer codes used to derive the results are appropriate for this application.

C.2 Submersion DCF.xls: Air Submersion External Dose Factors

1. Purpose

The purpose of this workbook, *Submersion DCF.xls*, is to convert the fluence calculations using the SCALE 4.3 code to units of effective dose equivalent for each of 18 gamma-ray energy groups. The conversion is done with the fluence-to-dose factors calculated using the methodology in ANSI/ANS-6.1.1-1991, *Neutron and Gamma-Ray Fluence-to-Dose Factors*. The doses are calculated for semi-infinite slab (or cloud), main drift and emplacement drift geometries. This worbook calculates the geometry factors, or dose ratios, between drift geometries and the semi-infinite slab. A sensitivity analysis assesses the impacts of using different fluence-to-dose factor exposure geometries. A comparison is made between the use of 1991 and 1977 fluence-to-dose factors from ANSI/ANS-6.1.1.

2. Organization and Function

There are five sheets (including this Introduction) within this workbook. The right-hand header identifies the name of the sheet. The function and calculations performed by each sheet, as well as any input and output values or links, are summarized in the following sections. The variable names that have been assigned to each sheet are identified. These are used to simplify the calculation formulas used in this workbook. The formulas themselves are described in each sheet. Color coding, shading, and text boxes are used throughout this workbook to report the calculations performed and identify the names and ranges of input and output cells.

2.1 Introduction

This sheet.

2.2 Fluence-to-Dose

This sheet is organized in three parts: air submersion fluence-to-dose calculations for semi-infinite slab, main drift, and emplacement drift geometries, respectively. Each part consists of a table of gamma-ray energies corresponding to the 18 groups used in the SCALE 4.3 calculations, followed by the corresponding fluence-to-dose coefficients from ANS/ANS-6.1.1 for the exposure conditions that are appropriate for each geometry. The source of these values is a link from the *ANSI-ANS-6.1.1.xls* workbook (See C.4). The next set of numbers is an 18x18 array of gamma-ray fluences calculated using the SCALE 4.3 code. These fluences are calculated for a source strength of 10^6 photons/cm^3-sec in air with a dose point located 1 m above the concrete-air surface. The SCALE 4.3 output files that generated these numbers are: AIRSLAB1.OUT, AIRSLAB2.OUT, SUBM_MD1.OUT, SUBM_MD2.OUT, SUBM_ED1.OUT and SUBM_ED2.OUT. The last set of numbers is the dose for each energy group and is the result of a matrix multiplication between the 18-group fluence array and the 18 fluence-to-dose factors. For the semi-infinite slab geometry, there is one more calculation: the infinite slab dose is divided by 2 to obtain the semi-infinite slab dose. The dose arrays are used as input in the next sheet to calculate the geometry factors for the main and emplacement drifts.

The names of the arrays assigned to this sheet are:

Energy Groups	*Fluence-to-Dose Factors*	*Fluence Arrays*	*Calculated Doses*
Group_Number	ISO_Dose_Factors	Inf_Slab_Fluence	Semi_Inf_Slab_Dose
Upper_Energy	AP_PA_Dose_Factors	Main_Drift_Fluence	Main_Drift_Dose
Mean_Energy		Empl_Drift_Fluence	Empl_Drift_Dose

The named range can be highlighted by selecting the array name from the pulldown menu box on the Excel formula bar.

2.3 Geometry Factors

This sheet computes the geometry factors for the main and emplacement drift geometries. The geometry factors are used to investigate the difference in dose rates from air submersion in the main or emplacement drift relative to submersion in a semi-infinite cloud. The sheet starts with a table of gamma-ray energies corresponding to the 18 groups used in the SCALE 4.3 calculations, followed by the summary of the semi-infinite slab, main drift, and emplacement drift doses calculated on the previous sheet. The next two columns are the geometry factors calculated for the main and emplacement drifts, respectively. The geometry factor is calculated as the ratio of the main or emplacement drift dose to the semi-infinite slab dose. The final column is a calculation of the difference between main and emplacement drift geometry factors.

The names of the arrays assigned to this sheet are Main_Drift_GF and Empl_Drift_GF, where GF stands for Geometry Factor. The named range can be highlighted by selecting the array name from the pulldown menu box on the Excel formula bar.

2.4 Sensitivity Analysis

This sheet compares the results obtained in the previous sheets under assumptions of AP-PA exposure geometry in the drifts with the results that would be obtained under AP and LAT exposure geometries. Of all the exposure geometries in ANSI/ANS-6.1.1, AP yields the highest dose and LAT the lowest. The AP exposure geometry would only apply for a receptor facing the entrance of the drift. At this location, the receptor would only be exposed to one half of the volume of contaminated air compared to a location half way down the drift. For this exposure condition, the AP geometry factors should be reduced by a factor of 2. The LAT exposure geometry would more appropriately apply to a receptor facing the walls of the drift. The greatest differences in estimated geometry factors are found at the lowest gamma-ray energies. The drift diameter had no effect on the calculated differences between exposure geometries.

2.5 1991 vs 1977 Standard

This sheet compares the differences in dose obtained by using 1991 vs.1977 dose-to-fluence factors from ANSI/ANS-6.1.1 for the semi-infinite slab, main drift, and emplacement drift geometries. The greatest differences are found at the lower gamma-ray energy groups, because this is where the 1991 and 1977 versions of ANSI/ANS-6.1.1 fluence-to-dose factors exhibit the greatest deviation.

3. Results and Conclusions

Geometry factors for the AP-PA exposure geometry in the drifts range from 0.016 for the highest energy group in the emplacement drifts to 0.72 for the lowest energy group in the main drift. For any given energy group, the difference in geometry factors between main and emplacement drifts is about 40%, except for the lowest energy group (30%).

4. Workbook Links

The following named ranges from *ANSI-ANS-6.1.1.xls* are input links for this workbook: Group_Number, Upper_Energy, Mean_Energy, AP_Dose_Factors, AP_PA_Dose_Factors, ISO_Dose_Factors, LAT_Dose_Factors, and Old_Dose_Factors.

The following named ranges from this workbook are input links for *Radionuclide DCF.xls*: Semi_Inf_Slab_Dose, Main_Drift_Dose, Main_Drift_Dose_77, and Empl_Drift_Dose.

Author: E. R. Faillace - last modified 8/22/2000

Air Submersion Fluence-to-Dose Calculations for Semi-Infinite Cloud Geometry

Gamma-Ray Energy (E)			Isotropic Fluence-to-Dose Factor	Fluence Summary: Output from 18-Group SCALE Calculation for Infinite Air Slab Submersion (Node 1) - Groups 1 through 8							
Energy Group	Upper (eV)	Mean (MeV)	mrem/hr per γ/cm^2-sec	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1	1.00E+07	9.00E+00	7.08E-03	4.04E+10	2.68E+09	2.85E+09	2.11E+09	2.46E+09	1.45E+09	1.72E+09	1.40E+09
2	8.00E+06	7.25E+00	5.88E-03	0.00E+00	3.72E+10	3.47E+09	2.47E+09	2.80E+09	1.63E+09	1.90E+09	1.54E+09
3	6.50E+06	5.75E+00	4.87E-03	0.00E+00	0.00E+00	3.40E+10	2.98E+09	3.23E+09	1.82E+09	2.09E+09	1.67E+09
4	5.00E+06	4.50E+00	4.02E-03	0.00E+00	0.00E+00	0.00E+00	3.00E+10	3.83E+09	2.08E+09	2.32E+09	1.82E+09
5	4.00E+06	3.50E+00	3.32E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.71E+10	2.45E+09	2.64E+09	2.00E+09
6	3.00E+06	2.75E+00	2.75E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.33E+10	3.06E+09	2.24E+09
7	2.50E+06	2.25E+00	2.35E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.13E+10	2.52E+09
8	2.00E+06	1.83E+00	1.99E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.90E+10
9	1.66E+06	1.50E+00	1.68E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	1.33E+06	1.17E+00	1.35E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	1.00E+06	9.00E-01	1.06E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	8.00E+05	7.00E-01	8.34E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	6.00E+05	5.00E-01	5.92E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	4.00E+05	3.50E-01	4.04E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	3.00E+05	2.50E-01	2.78E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.00E+05	1.50E-01	1.54E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	1.00E+05	7.50E-02	8.28E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	5.00E+04	3.00E-02	4.80E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1.00E+04										

1 eV = 10^{-6} MeV

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.1.1.xls*. The most appropriate Fluence-to-Dose Factors for this calculation are those for the isotropic (ISO) exposure geometry, since the gamma-rays are incident on the receptor from all directions in an infinite cloud. The values are linked to the **ISO** sheet in *ANSI-ANS-6.1.1.xls*, and the 1x18 array is named ISO_Dose_Factors. The first 8 energy groups of the Fluence Summary are presented on this page; the remaining 10 groups are presented on the following page. The Fluence Summary was created by cutting the values for the Total Flux, Node 1, from the Infinite Air Slab Submersion SCALE output (AIRSLAB1.OUT and AIRSLAB2.OUT) for each energy group and pasting them into this sheet. The resulting 18x18 array is named Inf_Slab_Fluence.

Air Submersion Fluence-to-Dose Calculations for Semi-Infinite Cloud Geometry (Continued)

Fluence Summary: Output from 18-Group SCALE Calculation
for Infinite Air Slab Submersion (Node 1) - Groups 9 through 18

Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	Semi Inf. Slab Dose mrem/hr
1.66E+09	2.17E+09	1.76E+09	2.44E+09	1.08E+10	5.65E+09	1.00E+10	3.06E+10	4.18E+10	1.83E+09	1.86E+08
1.81E+09	2.36E+09	1.91E+09	2.64E+09	9.40E+09	5.40E+09	9.62E+09	2.90E+10	3.96E+10	1.74E+09	1.48E+08
1.95E+09	2.53E+09	2.03E+09	2.81E+09	8.25E+09	5.18E+09	9.28E+09	2.77E+10	3.78E+10	1.66E+09	1.15E+08
2.09E+09	2.68E+09	2.14E+09	2.94E+09	7.26E+09	4.99E+09	9.01E+09	2.65E+10	3.63E+10	1.59E+09	8.80E+07
2.25E+09	2.83E+09	2.23E+09	3.05E+09	6.45E+09	4.82E+09	8.80E+09	2.56E+10	3.50E+10	1.54E+09	6.71E+07
2.44E+09	2.98E+09	2.31E+09	3.12E+09	5.87E+09	4.67E+09	8.67E+09	2.50E+10	3.42E+10	1.50E+09	5.17E+07
2.66E+09	3.15E+09	2.38E+09	3.17E+09	5.54E+09	4.57E+09	8.62E+09	2.47E+10	3.37E+10	1.48E+09	4.16E+07
2.99E+09	3.38E+09	2.48E+09	3.22E+09	5.31E+09	4.47E+09	8.60E+09	2.45E+10	3.35E+10	1.47E+09	3.33E+07
1.75E+10	3.74E+09	2.62E+09	3.30E+09	5.17E+09	4.37E+09	8.61E+09	2.44E+10	3.33E+10	1.46E+09	2.69E+07
0.00E+00	1.61E+10	2.93E+09	3.49E+09	5.12E+09	4.24E+09	8.65E+09	2.43E+10	3.32E+10	1.46E+09	2.07E+07
0.00E+00	0.00E+00	1.40E+10	3.87E+09	5.22E+09	4.12E+09	8.59E+09	2.43E+10	3.32E+10	1.46E+09	1.59E+07
0.00E+00	0.00E+00	0.00E+00	1.32E+10	5.57E+09	4.04E+09	8.12E+09	2.43E+10	3.32E+10	1.46E+09	1.24E+07
0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.30E+10	4.20E+09	7.36E+09	2.43E+10	3.33E+10	1.46E+09	9.01E+06
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.09E+10	6.90E+09	2.43E+10	3.33E+10	1.46E+09	6.44E+06
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.17E+10	2.43E+10	3.32E+10	1.46E+09	4.91E+06
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.44E+10	3.33E+10	1.46E+09	3.29E+06
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.40E+10	1.49E+09	1.44E+06
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E+09	4.90E+04

The highlighted 1x18 array is named Semi_Inf_Slab_Dose, and the underlying formula for each cell in the array is:

=MMULT(Inf_Slab_Fluence,ISO_Dose_Factors)/2

This formula calculates the semi-infinite cloud submersion dose by dividing the infinite cloud submersion dose for each energy group by 2. The infinite cloud submersion dose is the product of a matrix multiplication operation between the 18x18 Inf_Slab_Fluence array and the 1x18 ISO_Dose_Factors array. The arguments of the MMULT function are described on the previous page. See Excel Help for more information on the MMULT function.

Air Submersion Fluence-to-Dose Calculations for Main Drift Geometry

Gamma-Ray Energy (E)			AP-PA Fluence-to-Dose Factor	Fluence Summary: Output from 18-Group SCALE Calculation Main Drift Air Submersion, Radius = 381 cm, Receptor 1m Above Surface (Node 38) - Grp 1-8							
Energy Group	Upper (eV)	Mean (MeV)	mrem/hr per γ/cm^2-sec	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1	1.00E+07	9.00E+00	8.09E-03	4.80E+08	7.21E+05	1.03E+06	9.77E+05	1.49E+06	1.09E+06	1.56E+06	1.52E+06
2	8.00E+06	7.25E+00	6.81E-03	0.00E+00	4.79E+08	1.14E+06	1.12E+06	1.67E+06	1.23E+06	1.78E+06	1.73E+06
3	6.50E+06	5.75E+00	5.72E-03	0.00E+00	0.00E+00	4.79E+08	1.19E+06	1.89E+06	1.41E+06	2.00E+06	1.96E+06
4	5.00E+06	4.50E+00	4.79E-03	0.00E+00	0.00E+00	0.00E+00	4.78E+08	2.02E+06	1.53E+06	2.21E+06	2.18E+06
5	4.00E+06	3.50E+00	4.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.77E+08	1.60E+06	2.36E+06	2.37E+06
6	3.00E+06	2.75E+00	3.39E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.75E+08	2.33E+06	2.47E+06
7	2.50E+06	2.25E+00	2.93E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.75E+08	2.39E+06
8	2.00E+06	1.83E+00	2.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.73E+08
9	1.66E+06	1.50E+00	2.17E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	1.33E+06	1.17E+00	1.78E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	1.00E+06	9.00E-01	1.44E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	8.00E+05	7.00E-01	1.16E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	6.00E+05	5.00E-01	8.52E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	4.00E+05	3.50E-01	6.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	3.00E+05	2.50E-01	4.27E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.00E+05	1.50E-01	2.48E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	1.00E+05	7.50E-02	1.40E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	5.00E+04	3.00E-02	8.82E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1.00E+04										

1 eV = 10^{-6} MeV

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.1.1.xls*. The receptor is assumed to be 1 m above the base of the drift facing in the direction normal to the drift cross-section. The most appropriate Fluence-to-Dose Factors for this calculation are those for the anterior-posterior and posterior-anterior (AP-PA) exposure geometry, since the gamma-rays are incident on the receptor primarily from the front and back. The values are linked to the **AP-PA** sheet in *ANSI-ANS-6.1.1.xls*, and the 1x18 array is named AP_PA_Dose_Factors. The first 8 energy groups of the Fluence Summary are presented on this page; the remaining 10 groups are presented on the following page. The Fluence Summary was created by cutting the values for the Total Flux, Node 38, from the Main Drift Air Submersion SCALE output (SUBM_MD1.OUT and SUBM_MD2.OUT) for each energy group and pasting them into this sheet. The resulting 18x18 array is named Main_Drift_Fluence.

Air Submersion Fluence-to-Dose Calculations for Main Drift Geometry (Continued)

Fluence Summary: Output from 18-Group SCALE Calculation Main Drift Air Submersion, Radius = 381 cm, Receptor 1m Above Surface (Node 38) - Grp 9-18										Main Drift Dose mrem/hr
Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	
2.12E+06	3.33E+06	3.22E+06	5.30E+06	6.61E+07	2.72E+07	4.95E+07	1.17E+08	4.68E+07	6.13E+05	4.07E+06
2.43E+06	3.83E+06	3.72E+06	6.15E+06	5.70E+07	2.64E+07	4.87E+07	1.12E+08	4.45E+07	5.84E+05	3.44E+06
2.76E+06	4.37E+06	4.26E+06	7.08E+06	4.93E+07	2.63E+07	4.93E+07	1.09E+08	4.35E+07	5.70E+05	2.91E+06
3.08E+06	4.92E+06	4.80E+06	8.03E+06	4.23E+07	2.65E+07	5.12E+07	1.08E+08	4.32E+07	5.66E+05	2.45E+06
3.38E+06	5.46E+06	5.33E+06	8.98E+06	3.59E+07	2.70E+07	5.45E+07	1.10E+08	4.37E+07	5.73E+05	2.07E+06
3.60E+06	5.90E+06	5.77E+06	9.77E+06	3.10E+07	2.76E+07	5.90E+07	1.13E+08	4.51E+07	5.92E+05	1.76E+06
3.67E+06	6.17E+06	6.11E+06	1.03E+07	2.82E+07	2.84E+07	6.42E+07	1.19E+08	4.72E+07	6.20E+05	1.54E+06
3.45E+06	6.29E+06	6.39E+06	1.08E+07	2.63E+07	2.90E+07	7.06E+07	1.26E+08	5.00E+07	6.58E+05	1.34E+06
4.72E+08	6.02E+06	6.54E+06	1.11E+07	2.52E+07	2.94E+07	7.79E+07	1.35E+08	5.34E+07	7.02E+05	1.17E+06
0.00E+00	4.72E+08	6.17E+06	1.14E+07	2.50E+07	2.95E+07	8.80E+07	1.48E+08	5.83E+07	7.67E+05	9.84E+05
0.00E+00	0.00E+00	4.69E+08	1.07E+07	2.49E+07	2.88E+07	9.61E+07	1.65E+08	6.39E+07	8.41E+05	8.18E+05
0.00E+00	0.00E+00	0.00E+00	4.69E+08	2.38E+07	2.75E+07	9.05E+07	1.89E+08	7.07E+07	9.32E+05	6.77E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.73E+08	2.49E+07	7.56E+07	2.27E+08	8.10E+07	1.07E+06	5.18E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.69E+08	5.71E+07	2.64E+08	9.26E+07	1.22E+06	3.85E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.82E+08	2.92E+08	1.05E+08	1.39E+06	2.93E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.57E+08	1.63E+08	2.15E+06	1.86E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.14E+08	7.71E+06	8.66E+04
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.98E+08	3.51E+04

The highlighted1x18 array is named Main_Drift_Dose; it is the product of a matrix multiplication operation between the 18x18 Main_Drift_Fluence array and the 1x18 AP_PA_Dose_Factors array. The underlying formula for Main_Drift_Dose is:

=MMULT(Main_Drift_Fluence,AP_PA_Dose_Factors)

The arguments of the MMULT function are described on the previous page. See Excel Help for more information on the MMULT function.

Air Submersion Fluence-to-Dose Calculations for Emplacement Drift Geometry

Gamma-Ray Energy (E)			AP-PA Fluence-to-Dose Factor	Fluence Summary: Output from 18-Group SCALE Calculation Empl. Drift Air Submersion, Radius = 255 cm, Receptor 1m Above Surface (Node 31) - Grp 1-8							
Energy Group	Upper (eV)	Mean (MeV)	mrem/hr per γ/cm^2-sec	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1	1.00E+07	9.00E+00	8.09E-03	3.46E+08	3.40E+05	5.29E+05	5.47E+05	8.33E+05	6.43E+05	9.20E+05	8.97E+05
2	8.00E+06	7.25E+00	6.81E-03	0.00E+00	3.46E+08	5.43E+05	6.01E+05	9.46E+05	7.10E+05	1.04E+06	1.02E+06
3	6.50E+06	5.75E+00	5.72E-03	0.00E+00	0.00E+00	3.46E+08	5.72E+05	1.05E+06	7.94E+05	1.17E+06	1.16E+06
4	5.00E+06	4.50E+00	4.79E-03	0.00E+00	0.00E+00	0.00E+00	3.45E+08	1.01E+06	8.55E+05	1.26E+06	1.27E+06
5	4.00E+06	3.50E+00	4.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.45E+08	8.10E+05	1.31E+06	1.37E+06
6	3.00E+06	2.75E+00	3.39E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.44E+08	1.19E+06	1.35E+06
7	2.50E+06	2.25E+00	2.93E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.44E+08	1.24E+06
8	2.00E+06	1.83E+00	2.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.43E+08
9	1.66E+06	1.50E+00	2.17E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	1.33E+06	1.17E+00	1.78E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	1.00E+06	9.00E-01	1.44E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	8.00E+05	7.00E-01	1.16E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	6.00E+05	5.00E-01	8.52E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	4.00E+05	3.50E-01	6.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	3.00E+05	2.50E-01	4.27E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.00E+05	1.50E-01	2.48E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	1.00E+05	7.50E-02	1.40E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	5.00E+04	3.00E-02	8.82E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1.00E+04	1 eV = 10^{-6} MeV									

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.1.1.xls*. The receptor is assumed to be 1 m above the base of the drift facing in the direction normal to the drift cross-section. The most appropriate Fluence-to-Dose Factors for this calculation are those for the anterior-posterior and posterior-anterior (AP-PA) exposure geometry, since the gamma-rays are incident on the receptor primarily from the front and back. The values are linked to the **AP-PA** sheet in *ANSI-ANS-6.1.1.xls*, and the 1x18 array is named AP_PA_Dose_Factors. The first 8 energy groups of the Fluence Summary are presented on this page; the remaining 10 groups are presented on the following page. The Fluence Summary was created by cutting the values for the Total Flux, Node 31, from the Emplacement Drift Air Submersion SCALE output (SUBM_ED1.OUT and SUBM_ED2.OUT) for each energy group and pasting them into this sheet. The resulting 18x18 array is named Empl_Drift_Fluence.

Air Submersion Fluence-to-Dose Calculations for Emplacement Drift Geometry (Continued)

Fluence Summary: Output from 18-Group SCALE Calculation
Empl. Drift Air Submersion, Radius = 255 cm, Receptor 1m Above Surface (Node 31) - Grp 9-18

Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	Empl. Drift Dose mrem/hr
1.25E+06	1.98E+06	1.89E+06	3.16E+06	4.28E+07	1.77E+07	3.29E+07	7.73E+07	3.05E+07	3.47E+05	2.92E+06
1.44E+06	2.28E+06	2.18E+06	3.66E+06	3.67E+07	1.72E+07	3.24E+07	7.35E+07	2.90E+07	3.31E+05	2.47E+06
1.63E+06	2.60E+06	2.50E+06	4.20E+06	3.16E+07	1.71E+07	3.30E+07	7.17E+07	2.83E+07	3.23E+05	2.08E+06
1.81E+06	2.92E+06	2.82E+06	4.75E+06	2.69E+07	1.72E+07	3.43E+07	7.12E+07	2.81E+07	3.21E+05	1.76E+06
1.98E+06	3.22E+06	3.15E+06	5.29E+06	2.26E+07	1.74E+07	3.66E+07	7.21E+07	2.85E+07	3.25E+05	1.48E+06
2.08E+06	3.45E+06	3.42E+06	5.72E+06	1.92E+07	1.78E+07	3.97E+07	7.45E+07	2.94E+07	3.36E+05	1.26E+06
2.07E+06	3.60E+06	3.61E+06	6.04E+06	1.72E+07	1.81E+07	4.32E+07	7.81E+07	3.08E+07	3.52E+05	1.10E+06
1.85E+06	3.61E+06	3.75E+06	6.31E+06	1.58E+07	1.84E+07	4.75E+07	8.29E+07	3.26E+07	3.73E+05	9.59E+05
3.43E+08	3.25E+06	3.80E+06	6.56E+06	1.50E+07	1.84E+07	5.23E+07	8.87E+07	3.48E+07	3.98E+05	8.34E+05
0.00E+00	3.42E+08	3.41E+06	6.65E+06	1.47E+07	1.82E+07	5.89E+07	9.74E+07	3.80E+07	4.35E+05	7.01E+05
0.00E+00	0.00E+00	3.41E+08	6.03E+06	1.45E+07	1.74E+07	6.38E+07	1.08E+08	4.16E+07	4.78E+05	5.82E+05
0.00E+00	0.00E+00	0.00E+00	3.42E+08	1.38E+07	1.63E+07	5.88E+07	1.25E+08	4.61E+07	5.30E+05	4.80E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.44E+08	1.44E+07	4.72E+07	1.50E+08	5.28E+07	6.08E+05	3.67E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.42E+08	3.38E+07	1.74E+08	6.02E+07	6.96E+05	2.72E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.50E+08	1.90E+08	6.85E+07	7.93E+05	2.06E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.64E+08	1.06E+08	1.22E+06	1.30E+05
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.36E+08	4.52E+06	6.14E+04
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.07E+08	2.70E+04

The highlighted1x18 array is named Empl_Drift_Dose; it is the product of a matrix multiplication operation between the 18x18 Empl_Drift_Fluence array and the 1x18 AP_PA_Dose_Factors array. The underlying formula for Empl_Drift_Dose is:

=MMULT(Main_Drift_Fluence,AP_PA_Dose_Factors)

The arguments of the MMULT function are described on the previous page. See Excel Help for more information on the MMULT function.

Air Submersion Geometry Factor Calculation for Main Drift and Emplacement Drift

Gamma-Ray Energy (E)			Semi Inf.	Main Drift	Empl. Drift	Main Drift	Empl. Drift
Energy Group	Upper (eV)	Mean (MeV)	Slab Dose mrem/hr	Dose mrem/hr	Dose mrem/hr	Geometry Factor	Geometry Factor
1	1.00E+07	9.00E+00	1.86E+08	4.07E+06	2.92E+06	2.18E-02	1.57E-02
2	8.00E+06	7.25E+00	1.48E+08	3.44E+06	2.47E+06	2.33E-02	1.67E-02
3	6.50E+06	5.75E+00	1.15E+08	2.91E+06	2.08E+06	2.53E-02	1.81E-02
4	5.00E+06	4.50E+00	8.80E+07	2.45E+06	1.76E+06	2.79E-02	2.00E-02
5	4.00E+06	3.50E+00	6.71E+07	2.07E+06	1.48E+06	3.08E-02	2.21E-02
6	3.00E+06	2.75E+00	5.17E+07	1.76E+06	1.26E+06	3.41E-02	2.44E-02
7	2.50E+06	2.25E+00	4.16E+07	1.54E+06	1.10E+06	3.71E-02	2.65E-02
8	2.00E+06	1.83E+00	3.33E+07	1.34E+06	9.59E+05	4.03E-02	2.88E-02
9	1.66E+06	1.50E+00	2.69E+07	1.17E+06	8.34E+05	4.35E-02	3.11E-02
10	1.33E+06	1.17E+00	2.07E+07	9.84E+05	7.01E+05	4.75E-02	3.38E-02
11	1.00E+06	9.00E-01	1.59E+07	8.18E+05	5.82E+05	5.14E-02	3.66E-02
12	8.00E+05	7.00E-01	1.24E+07	6.77E+05	4.80E+05	5.46E-02	3.87E-02
13	6.00E+05	5.00E-01	9.01E+06	5.18E+05	3.67E+05	5.75E-02	4.07E-02
14	4.00E+05	3.50E-01	6.44E+06	3.85E+05	2.72E+05	5.98E-02	4.22E-02
15	3.00E+05	2.50E-01	4.91E+06	2.93E+05	2.06E+05	5.96E-02	4.19E-02
16	2.00E+05	1.50E-01	3.29E+06	1.86E+05	1.30E+05	5.65E-02	3.95E-02
17	1.00E+05	7.50E-02	1.44E+06	8.66E+04	6.14E+04	6.00E-02	4.25E-02
18	5.00E+04	3.00E-02	4.90E+04	3.51E+04	2.70E+04	7.15E-01	5.51E-01
	1.00E+04						

1 eV = 10^{-6} MeV

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.11.xls*. The three dose columns are copies of the results from the **Fluence-to-Dose** sheet of this workbook and are 1x18 arrays named Semi_Inf_Slab_Dose, Main_Drift_Dose, and

The first highlighted 1x18 array is the geometry factor for the Main Drift and is named Main_Drift_GF. The underlying formula for Main_Drift_GF is:

=Main_Drift_Dose/Semi_Inf_Slab_Dose

The second highlighted 1x18 array is the geometry factor for the Emplacement Drift and is named Empl_Drift_GF. The underlying formula for Empl_Drift_GF is:

=Empl_Drift_Dose/Semi_Inf_Slab_Dose

Sensitivity of Submersion Dose Geometry Factors to the Assumed Exposure Geometry

Energy Group	Emplacement Drift Exposure Geometry AP-PA	AP	Difference: (AP-APPA) / APPA
1	1.57E-02	1.59E-02	1.4%
2	1.67E-02	1.70E-02	1.9%
3	1.81E-02	1.85E-02	2.2%
4	2.00E-02	2.04E-02	2.4%
5	2.21E-02	2.26E-02	2.6%
6	2.44E-02	2.51E-02	2.8%
7	2.65E-02	2.73E-02	3.1%
8	2.88E-02	2.98E-02	3.5%
9	3.11E-02	3.23E-02	4.0%
10	3.38E-02	3.54E-02	4.8%
11	3.66E-02	3.87E-02	5.7%
12	3.87E-02	4.13E-02	6.6%
13	4.07E-02	4.39E-02	7.8%
14	4.22E-02	4.60E-02	9.0%
15	4.19E-02	4.60E-02	9.6%
16	3.95E-02	4.33E-02	9.7%
17	4.25E-02	4.91E-02	15.5%
18	5.51E-01	7.21E-01	30.7%

Energy Group	Main Drift Exposure Geometry AP-PA	AP	Difference: (AP-APPA) / APPA
1	2.18E-02	2.22E-02	1.4%
2	2.33E-02	2.37E-02	1.9%
3	2.53E-02	2.59E-02	2.2%
4	2.79E-02	2.86E-02	2.4%
5	3.08E-02	3.17E-02	2.6%
6	3.41E-02	3.51E-02	2.9%
7	3.71E-02	3.82E-02	3.2%
8	4.03E-02	4.18E-02	3.6%
9	4.35E-02	4.53E-02	4.1%
10	4.75E-02	4.98E-02	4.8%
11	5.14E-02	5.44E-02	5.7%
12	5.46E-02	5.82E-02	6.7%
13	5.75E-02	6.20E-02	7.9%
14	5.98E-02	6.52E-02	9.0%
15	5.96E-02	6.54E-02	9.7%
16	5.65E-02	6.21E-02	9.8%
17	6.00E-02	6.93E-02	15.5%
18	7.15E-01	9.35E-01	30.7%

Energy Group	Emplacement Drift Exposure Geometry AP-PA	LAT	Difference: (LAT-APPA) / APPA
1	1.57E-02	1.41E-02	-10.2%
2	1.67E-02	1.48E-02	-11.1%
3	1.81E-02	1.59E-02	-12.4%
4	2.00E-02	1.72E-02	-14.0%
5	2.21E-02	1.86E-02	-15.8%
6	2.44E-02	2.00E-02	-17.8%
7	2.65E-02	2.13E-02	-19.7%
8	2.88E-02	2.25E-02	-21.7%
9	3.11E-02	2.37E-02	-23.7%
10	3.38E-02	2.49E-02	-26.3%
11	3.66E-02	2.60E-02	-29.0%
12	3.87E-02	2.65E-02	-31.5%
13	4.07E-02	2.66E-02	-34.7%
14	4.22E-02	2.63E-02	-37.8%
15	4.19E-02	2.51E-02	-40.2%
16	3.95E-02	2.25E-02	-42.9%
17	4.25E-02	2.23E-02	-47.5%
18	5.51E-01	1.96E-01	-64.5%

Energy Group	Main Drift Exposure Geometry AP-PA	LAT	Difference: (LAT-APPA) / APPA
1	2.18E-02	1.96E-02	-10.3%
2	2.33E-02	2.07E-02	-11.3%
3	2.53E-02	2.22E-02	-12.5%
4	2.79E-02	2.40E-02	-14.1%
5	3.08E-02	2.59E-02	-16.0%
6	3.41E-02	2.80E-02	-18.0%
7	3.71E-02	2.97E-02	-19.8%
8	4.03E-02	3.15E-02	-21.8%
9	4.35E-02	3.31E-02	-23.9%
10	4.75E-02	3.49E-02	-26.5%
11	5.14E-02	3.64E-02	-29.2%
12	5.46E-02	3.73E-02	-31.7%
13	5.75E-02	3.74E-02	-34.9%
14	5.98E-02	3.71E-02	-37.9%
15	5.96E-02	3.56E-02	-40.3%
16	5.65E-02	3.22E-02	-43.0%
17	6.00E-02	3.15E-02	-47.5%
18	7.15E-01	2.54E-01	-64.5%

A sensitivity analysis is performed to assess the impact of the exposure geometry used for exposures in drifts. The Geometry Factors (GFs) for main and emplacement drifts are calculated using the anterior-posterior (AP, top tables) and lateral (LAT, bottom tables) exposure geometries. The underlying equations use the MMULT function, as shown in the **Fluence-to-Dose** sheet, to obtain the drift dose; this is divided by the semi-infinite cloud dose to obtain the GF. The results are then compared by calculating the percent difference from the GFs based on the AP-PA exposure geometry. This difference, as expected, is greatest at the lowest energy levels, and ranges from about one third higher (AP) to about three times lower (LAT).

Comparison of Results Using ANSI/ANS-6.1.1-1991 vs ANSI/ANS-6.1.1-1977

Energy Group	Semi-Infinite Slab ANSI/ANS-6.1.1 1991	1977	Difference '77-'91 / '91
1	1.86E+08	2.47E+08	32.8%
2	1.48E+08	2.03E+08	37.3%
3	1.15E+08	1.64E+08	42.4%
4	8.80E+07	1.30E+08	48.1%
5	6.71E+07	1.04E+08	54.8%
6	5.17E+07	8.35E+07	61.6%
7	4.16E+07	6.98E+07	67.7%
8	3.33E+07	5.82E+07	74.7%
9	2.69E+07	4.90E+07	82.3%
10	2.07E+07	4.00E+07	92.8%
11	1.59E+07	3.26E+07	105.1%
12	1.24E+07	2.70E+07	117.5%
13	9.01E+06	2.10E+07	133.1%
14	6.44E+06	1.63E+07	152.9%
15	4.91E+06	1.30E+07	165.2%
16	3.29E+06	9.35E+06	184.3%
17	1.44E+06	4.83E+06	234.1%
18	4.90E+04	5.94E+05	1110.8%

Energy Group	Main Drift ANSI/ANS-6.1.1 1991	1977	Difference '77-'91 / '91
1	4.07E+06	4.46E+06	9.7%
2	3.44E+06	3.83E+06	11.2%
3	2.91E+06	3.29E+06	13.0%
4	2.45E+06	2.81E+06	14.7%
5	2.07E+06	2.43E+06	17.1%
6	1.76E+06	2.10E+06	19.1%
7	1.54E+06	1.86E+06	20.6%
8	1.34E+06	1.64E+06	22.3%
9	1.17E+06	1.45E+06	24.3%
10	9.84E+05	1.25E+06	27.2%
11	8.18E+05	1.07E+06	30.9%
12	6.77E+05	9.15E+05	35.2%
13	5.18E+05	7.23E+05	39.5%
14	3.85E+05	5.72E+05	48.6%
15	2.93E+05	4.43E+05	51.1%
16	1.86E+05	2.92E+05	57.4%
17	8.66E+04	1.63E+05	88.2%
18	3.51E+04	2.32E+05	559.8%

Energy Group	Emplacement Drift ANSI/ANS-6.1.1 1991	1977	Difference '77-'91 / '91
1	2.92E+06	3.20E+06	9.6%
2	2.47E+06	2.74E+06	11.1%
3	2.08E+06	2.35E+06	12.8%
4	1.76E+06	2.01E+06	14.6%
5	1.48E+06	1.73E+06	17.0%
6	1.26E+06	1.50E+06	18.9%
7	1.10E+06	1.33E+06	20.4%
8	9.59E+05	1.17E+06	22.1%
9	8.34E+05	1.03E+06	24.0%
10	7.01E+05	8.89E+05	26.9%
11	5.82E+05	7.59E+05	30.6%
12	4.80E+05	6.47E+05	34.8%
13	3.67E+05	5.10E+05	39.1%
14	2.72E+05	4.03E+05	48.3%
15	2.06E+05	3.11E+05	50.8%
16	1.30E+05	2.04E+05	57.1%
17	6.14E+04	1.15E+05	87.5%
18	2.70E+04	1.78E+05	559.8%

A comparison was made to investigate the differences in dose obtained by using 1991 vs. 1977 dose-to-fluence factors from ANSI/ANS-6.1.1. The first table compares the Semi_Inf_Slab_Dose array from the **Fluence-to-Dose** sheet with the Inf_Slab_Fluence converted to dose using the 1977 fluence-to dose factors (Old_Dose_Factors) from the **1977 Factors** sheet of the *ANSI-ANS-6.1.1.xls* workbook. The resulting array is named Semi_Inf_Slab_Dose_77, with an underlying formula of:

=MMULT(Inf_Slab_Fluence,'ANSI-ANS-6.1.1.xls'!Old_Dose_Factors)/2

The last column in the table is the percent difference between the 1991 and 1977 values.

The other two tables perform similar calculations targeted to main and emplacement drift dose factors, respectively.

The greatest differences are found at the lower gamma-ray energy groups, because this is where the 1991 and 1977 versions of ANSI/ANS-6.1.1 fluence-to-dose factors exhibit the greatest deviation. As expected, the differences by energy group are the about the same in the main and emplacement drift comparisons due to the use of the AP-PA exposure geometry in both cases. However, the differences in the semi-infinite slab comparison are significantly greater. This is because the ISO exposure geometry dose-to-fluence factors are lower than the AP-PA factors, which in turn are lower than the 1977 factors.

C. 3 Surface DCF.xls: Contaminated Surface External Dose Factors

1. Purpose

The purpose of this workbook, *Surface DCF.xls*, is to convert the fluence calculations using the SCALE 4.3 code to units of effective dose equivalent for each of 18 gamma-ray energy groups. The conversion is done with the fluence-to-dose factors calculated using the methodology in ANSI/ANS-6.1.1-1991, *Neutron and Gamma-Ray Fluence-to-Dose Factors*. The doses are calculated for infinite plane, main drift and emplacement drift geometries. This worbook calculates the geometry factors, or dose ratios, between drift geometries and infinite plane. A sensitivity analysis assesses the impacts of using different fluence-to-dose factor exposure geometries. A comparison is made between the use of 1991 and 1977 fluence-to-dose factors from ANSI/ANS-6.1.1.

2. Organization and Function

There are five sheets (including this Introduction) within this workbook. The right-hand header identifies the name of the sheet. The function and calculations performed by each sheet, as well as any input and output values or links, are summarized in the following sections. The variable names that have been assigned to each sheet are identified. These are used to simplify the calculation formulas used in this workbook. The formulas themselves are described in each sheet. Color coding, shading, and text boxes are used throughout this workbook to report the calculations performed and identify the names and ranges of input and output cells.

2.1 Introduction

This sheet.

2.2 Fluence-to-Dose

This sheet is organized in three parts: surface contamination fluence-to-dose calculations for infinite plane, main drift and emplacement drift geometries, respectively. Each part consists of a table of gamma-ray energies corresponding to the 18 groups used in the SCALE 4.3 calculations, followed by the corresponding fluence-to-dose coefficients from ANS ANS 6.1.1 for the exposure conditions that are appropriate for each geometry. The source of these values is a link from the ANSI-ANS-6.1.1.xls workbook. The next set of numbers is an 18x18 array of gamma-ray fluences calculated using the SCALE 4.3 code. These fluences are calculated for a surface source strength of 10^6 photons/cm^2-sec at the concrete-air interface with a dose point located 1 m above the surface. The SCALE 4.3 output files that generated these numbers are: INFPLANE.OUT, SURF_MD1.OUT, SURF_MD2.OUT, SURF_ED1.OUT and SURF_ED2.OUT. The last set of numbers is the dose for each energy group and is the result of a matrix multiplication between the 18-group fluence array and the 18 fluence-to-dose factors. The dose arrays are used as input in the next sheet to calculate the geometry factors for the main and emplacement drifts.

The names of the arrays assigned to this sheet are:

Energy Groups	*Fluence-to-Dose Factors*	*Fluence Arrays*	*Calculated Doses*
Group_Number	ROT_Dose_Factors	Inf_Plane_Fluence	Inf_Plane_Dose
Upper_Energy	AP_PA_Dose_Factors	Main_Drift_Fluence	Main_Drift_Dose
Mean_Energy		Empl_Drift_Fluence	Empl_Drift_Dose

The named range can be highlighted by selecting the array name from the pulldown menu box on the Excel formula bar.

2.3 Geometry Factors

This sheet computes the geometry factors for the main and emplacement drift geometries. The geometry factors are used to investigate the difference in dose rates from surface contamination in the main or emplacement drift relative to surface contamination on an infinite plane. The sheet starts with a table of gamma-ray energies corresponding to the 18 groups used in the SCALE 4.3 calculations, followed by the summary of the infinite plane, main drift, and emplacement drift doses calculated on the previous sheet. The next two columns are the geometry factors calculated for the main and emplacement drifts, respectively. The geometry factor is calculated as the ratio of the main or emplacement drift dose to the infinite plane dose. The final column is a calculation of the difference between main and emplacement drift geometry factors.

The names of the arrays assigned to this sheet are Main_Drift_GF and Empl_Drift_GF, where GF stands for Geometry Factor. The named range can be highlighted by selecting the array name from the pulldown menu box on the Excel formula bar.

2.4 Sensitivity Analysis

This sheet compares the results obtained in the previous sheets under assumptions of AP-PA exposure geometry in the drifts with the results that would be obtained under AP and LAT exposure geometries. Of all the exposure geometries in ANSI ANS 6.1.1, AP yields the highest dose and LAT the lowest. The AP exposure geometry would only apply for a receptor facing the entrance of the drift. At this location, the receptor would only be exposed to one half of the source of contaminated surface compared to a location midway down the drift. For this exposure condition, the AP geometry factors should be reduced by a factor of 2. The LAT exposure geometry would more appropriately apply to a receptor facing the walls of the drift, but would underestimate the contributions of the source directly in front of the receptor. The greatest differences in estimated geometry factors are found at the lowest gamma-ray energies. The drift diameter had no effect on the calculated differences between exposure geometries.

2.5 1991 vs 1977 Standard

This sheet compares the differences in dose obtained by using 1991 vs.1977 dose-to-fluence factors from ANSI/ANS-6.1.1 for the infinite plane, main drift, and emplacement drift geometries. The greatest differences are found at the lower gamma-ray energy groups, because this is where the 1991 and 1977 versions of ANSI/ANS-6.1.1 fluence-to-dose factors exhibit the greatest deviation.

3. Results and Conclusions

Geometry factors for the AP-PA exposure geometry in the drifts range from 0.80 for the highest energy group in the emplacement drifts to 1.8 for the lowest energy group in the main drift. This implies that, for gamma-ray energies below 2 MeV, the doses from exposures to surface contamination in the drifts will be equal to or HIGHER relative to an infinite plane geometry. This is due to the assumption that the contamination is deposited uniformly on the drift walls and surrounds the receptor. In the infinite plane source, the contamination is located underneath the receptor. For any given energy group, the difference in geometry factors between main and emplacement drifts ranged from 5.1% to 7.3%, except for the lowest energy group (1.2%).

4. Workbook Links

The following named ranges from ANSI-ANS-6.1.1.xls are input links for this workbook: Group_Number, Upper_Energy, Mean_Energy, AP_Dose_Factors, AP_PA_Dose_Factors, LAT_Dose_Factors, ROT_Dose_Factors and Old_Dose_Factors.

The following named ranges from this workbook are input links for Radionuclide DCF.xls: Inf_Plane_Dose, Main_Drift_Dose, Main_Drift_Dose_77, and Empl_Drift_Dose.

Author: E. R. Faillace - last modified 8/22/2000

Surface Fluence-to-Dose Calculations for Infinite Plane Geometry

Gamma-Ray Energy (E)			Rotational Fluence-to-Dose Factor	Fluence Summary: Output from 18-Group SCALE Calculation Infinite Plane Source, Receptor 1m Above Surface (Node 31) - Groups 1 through 8							
Energy Group	Upper (eV)	Mean (MeV)	mrem/hr per g/cm^2-sec	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1	1.00E+07	9.00E+00	7.52E-03	2.35E+06	2.67E+04	2.87E+04	2.17E+04	2.59E+04	1.57E+04	1.90E+04	1.58E+04
2	8.00E+06	7.25E+00	6.24E-03	0.00E+00	2.35E+06	3.81E+04	2.76E+04	3.20E+04	1.90E+04	2.26E+04	1.87E+04
3	6.50E+06	5.75E+00	5.18E-03	0.00E+00	0.00E+00	2.34E+06	3.69E+04	4.07E+04	2.35E+04	2.74E+04	2.23E+04
4	5.00E+06	4.50E+00	4.31E-03	0.00E+00	0.00E+00	0.00E+00	2.32E+06	5.40E+04	2.98E+04	3.38E+04	2.70E+04
5	4.00E+06	3.50E+00	3.59E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.31E+06	3.96E+04	4.33E+04	3.34E+04
6	3.00E+06	2.75E+00	3.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.28E+06	5.60E+04	4.18E+04
7	2.50E+06	2.25E+00	2.60E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.27E+06	5.17E+04
8	2.00E+06	1.83E+00	2.22E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.24E+06
9	1.66E+06	1.50E+00	1.89E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	1.33E+06	1.17E+00	1.54E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	1.00E+06	9.00E-01	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	8.00E+05	7.00E-01	9.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	6.00E+05	5.00E-01	7.01E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	4.00E+05	3.50E-01	4.84E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	3.00E+05	2.50E-01	3.37E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.00E+05	1.50E-01	1.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	1.00E+05	7.50E-02	1.01E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	5.00E+04	3.00E-02	5.88E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1.00E+04										

1 eV = 10^{-6} MeV

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.1.1.xls*. The most appropriate Fluence-to-Dose Factors for this calculation are those for the rotational (ROT) exposure geometry, since the gamma-rays are incident on the receptor from all sides in an infinite plane. The values are linked to the **ROT** sheet in *ANSI-ANS-6.1.1.xls*, and the 1x18 array is named ROT_Dose_Factors. The first 8 energy groups of the Fluence Summary are presented on this page; the remaining 10 groups are presented on the following page. The Fluence Summary was created by cutting the values for the Total Flux, Node 31, from the Infinite Plane Source SCALE output (INFPLANE.OUT) for each energy group and pasting them into this sheet. The resulting 18x18 array is named Inf_Plane_Fluence.

Surface Fluence-to-Dose Calculations for Infinite Plane Geometry (Continued)

Fluence Summary: Output from 18-Group SCALE Calculation Infinite Plane Source, Receptor 1m Above Surface (Node 31) - Groups 9 through 18										Inf. Plane Dose mrem/hr
Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	
1.90E+04	2.52E+04	2.03E+04	2.76E+04	2.28E+05	7.77E+04	1.27E+05	2.50E+05	1.10E+05	2.98E+03	1.88E+04
2.24E+04	2.95E+04	2.38E+04	3.23E+04	1.97E+05	7.64E+04	1.27E+05	2.40E+05	1.05E+05	2.85E+03	1.56E+04
2.65E+04	3.47E+04	2.79E+04	3.79E+04	1.73E+05	7.71E+04	1.30E+05	2.36E+05	1.03E+05	2.80E+03	1.31E+04
3.15E+04	4.09E+04	3.27E+04	4.42E+04	1.52E+05	7.91E+04	1.36E+05	2.37E+05	1.04E+05	2.80E+03	1.09E+04
3.81E+04	4.84E+04	3.83E+04	5.15E+04	1.34E+05	8.25E+04	1.47E+05	2.43E+05	1.06E+05	2.83E+03	9.09E+03
4.63E+04	5.71E+04	4.44E+04	5.90E+04	1.23E+05	8.70E+04	1.62E+05	2.55E+05	1.11E+05	3.00E+03	7.63E+03
5.57E+04	6.66E+04	5.06E+04	6.62E+04	1.19E+05	9.19E+04	1.78E+05	2.70E+05	1.17E+05	3.17E+03	6.59E+03
6.86E+04	7.93E+04	5.84E+04	7.47E+04	1.21E+05	9.75E+04	1.98E+05	2.91E+05	1.25E+05	3.39E+03	5.64E+03
2.23E+06	9.62E+04	6.87E+04	8.53E+04	1.27E+05	1.04E+05	2.21E+05	3.15E+05	1.35E+05	3.66E+03	4.82E+03
0.00E+00	2.22E+06	8.64E+04	1.03E+05	1.42E+05	1.12E+05	2.55E+05	3.52E+05	1.50E+05	4.06E+03	3.94E+03
0.00E+00	0.00E+00	2.17E+06	1.29E+05	1.67E+05	1.22E+05	2.86E+05	4.00E+05	1.68E+05	4.55E+03	3.16E+03
0.00E+00	0.00E+00	0.00E+00	2.16E+06	2.04E+05	1.37E+05	2.84E+05	4.77E+05	1.94E+05	5.25E+03	2.53E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.18E+06	1.76E+05	2.80E+05	6.02E+05	2.36E+05	6.38E+03	1.84E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.10E+06	3.14E+05	7.55E+05	2.89E+05	7.81E+03	1.30E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.15E+06	9.33E+05	3.50E+05	9.46E+03	9.42E+02
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.66E+06	6.09E+05	1.60E+04	5.77E+02
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.67E+06	5.55E+04	2.74E+02
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.17E+06	6.89E+01

The highlighted1x18 array is named Inf_Plane_Dose; it is the product of a matrix multiplication operation between the 18x18 Inf_Plane_Fluence array and the 1x18 ROT_Dose_Factors array. The underlying formula for Inf_Plane_Dose is:

=MMULT(Inf_Plane_Fluence,ROT_Dose_Factors)

The arguments of the MMULT function are described on the previous page. See Excel Help for more information on the MMULT function.

Surface Fluence-to-Dose Calculations for Main Drift Geometry

Gamma-Ray Energy (E)			AP-PA Fluence-to-Dose Factor	Fluence Summary: Output from 18-Group SCALE Calculation Main Drift Surface, Radius = 381 cm, Receptor 1m Above Surface (Node 29) - Groups 1-8							
Energy Group	Upper (eV)	Mean (MeV)	mrem/hr per g/cm^2-sec	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1	1.00E+07	9.00E+00	8.09E-03	1.82E+06	4.65E+03	6.83E+03	7.10E+03	1.14E+04	8.71E+03	1.28E+04	1.29E+04
2	8.00E+06	7.25E+00	6.81E-03	0.00E+00	1.82E+06	7.50E+03	7.89E+03	1.27E+04	9.89E+03	1.46E+04	1.47E+04
3	6.50E+06	5.75E+00	5.72E-03	0.00E+00	0.00E+00	1.82E+06	8.32E+03	1.40E+04	1.10E+04	1.62E+04	1.64E+04
4	5.00E+06	4.50E+00	4.79E-03	0.00E+00	0.00E+00	0.00E+00	1.81E+06	1.43E+04	1.18E+04	1.78E+04	1.81E+04
5	4.00E+06	3.50E+00	4.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.81E+06	1.15E+04	1.88E+04	1.95E+04
6	3.00E+06	2.75E+00	3.39E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.80E+06	1.77E+04	2.01E+04
7	2.50E+06	2.25E+00	2.93E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.80E+06	1.85E+04
8	2.00E+06	1.83E+00	2.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.79E+06
9	1.66E+06	1.50E+00	2.17E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	1.33E+06	1.17E+00	1.78E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	1.00E+06	9.00E-01	1.44E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	8.00E+05	7.00E-01	1.16E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	6.00E+05	5.00E-01	8.52E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	4.00E+05	3.50E-01	6.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	3.00E+05	2.50E-01	4.27E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.00E+05	1.50E-01	2.48E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	1.00E+05	7.50E-02	1.40E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	5.00E+04	3.00E-02	8.82E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1.00E+04										

1 eV = 10^{-6} MeV

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.1.1.xls*. The receptor is assumed to be 1 m above the base of the drift facing in the direction normal to the drift cross-section. The most appropriate Fluence-to-Dose Factors for this calculation are those for the anterior-posterior and posterior-anterior (AP-PA) exposure geometry, since the gamma-rays are incident on the receptor primarily from the front and back. The values are linked to the **AP-PA** sheet in *ANSI-ANS-6.1.1.xls*, and the 1x18 array is named AP_PA_Dose_Factors. The first 8 energy groups of the Fluence Summary are presented on this page; the remaining 10 groups are presented on the following page. The Fluence Summary was created by cutting the values for the Total Flux, Node 29, from the Main Drift Ground SCALE output (SURF_MD1.OUT and SURF_MD2.OUT) for each energy group and pasting them into this sheet. The resulting 18x18 array is named Main_Drift_Fluence.

Surface Fluence-to-Dose Calculations for Main Drift Geometry (Continued)

Fluence Summary: Output from 18-Group SCALE Calculation
Main Drift Surface, Radius = 381 cm, Receptor 1m Above Surface (Node 29) - Groups 9-18

Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	Main Drift Dose mrem/hr
1.85E+04	2.99E+04	2.89E+04	4.66E+04	4.61E+05	1.81E+05	3.19E+05	7.66E+05	3.03E+05	4.00E+03	1.61E+04
2.11E+04	3.43E+04	3.33E+04	5.40E+04	4.01E+05	1.76E+05	3.12E+05	7.29E+05	2.88E+05	3.81E+03	1.37E+04
2.39E+04	3.89E+04	3.81E+04	6.20E+04	3.51E+05	1.76E+05	3.14E+05	7.08E+05	2.80E+05	3.70E+03	1.16E+04
2.66E+04	4.36E+04	4.29E+04	7.03E+04	3.06E+05	1.79E+05	3.22E+05	7.00E+05	2.76E+05	3.65E+03	9.88E+03
2.88E+04	4.80E+04	4.77E+04	7.85E+04	2.65E+05	1.83E+05	3.38E+05	7.04E+05	2.77E+05	3.66E+03	8.41E+03
3.04E+04	5.17E+04	5.17E+04	8.56E+04	2.35E+05	1.89E+05	3.61E+05	7.21E+05	2.84E+05	3.75E+03	7.22E+03
3.02E+04	5.37E+04	5.44E+04	9.06E+04	2.19E+05	1.96E+05	3.88E+05	7.50E+05	2.94E+05	3.89E+03	6.37E+03
2.76E+04	5.36E+04	5.64E+04	9.50E+04	2.09E+05	2.03E+05	4.23E+05	7.89E+05	3.09E+05	4.08E+03	5.59E+03
1.79E+06	4.96E+04	5.72E+04	9.84E+04	2.05E+05	2.08E+05	4.63E+05	8.36E+05	3.26E+05	4.31E+03	4.91E+03
0.00E+00	1.79E+06	5.13E+04	9.93E+04	2.07E+05	2.14E+05	5.19E+05	9.05E+05	3.51E+05	4.65E+03	4.18E+03
0.00E+00	0.00E+00	1.78E+06	8.98E+04	2.10E+05	2.16E+05	5.68E+05	9.90E+05	3.81E+05	5.04E+03	3.52E+03
0.00E+00	0.00E+00	0.00E+00	1.78E+06	2.02E+05	2.16E+05	5.55E+05	1.12E+06	4.19E+05	5.55E+03	2.94E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.83E+06	2.08E+05	5.08E+05	1.32E+06	4.78E+05	6.35E+03	2.29E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.80E+06	4.43E+05	1.55E+06	5.49E+05	7.31E+03	1.74E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.92E+06	1.75E+06	6.28E+05	8.37E+03	1.34E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.96E+06	9.59E+05	1.30E+04	8.68E+02
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.76E+06	4.23E+04	3.91E+02
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.39E+06	1.22E+02

The highlighted1x18 array is named Main_Drift_Dose; it is the product of a matrix multiplication operation between the 18x18 Main_Drift_Fluence array and the 1x18 AP_PA_Dose_Factors array. The underlying formula for Main_Drift_Dose is:

=MMULT(Main_Drift_Fluence,AP_PA_Dose_Factors)

The arguments of the MMULT function are described on the previous page. See Excel Help for more information on the MMULT function.

Surface Fluence-to-Dose Calculations for Emplacement Drift Geometry

Gamma-Ray Energy (E)			AP-PA Fluence-to-Dose Factor	Fluence Summary: Output from 18-Group SCALE Calculation Empl. Drift Surface, Radius = 255 cm, Receptor 1m Above Surface (Node 24) - Groups 1-8							
Energy Group	Upper (eV)	Mean (MeV)	mrem/hr per g/cm^2-sec	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
1	1.00E+07	9.00E+00	8.09E-03	1.70E+06	5.41E+03	6.91E+03	6.27E+03	9.45E+03	7.02E+03	1.01E+04	1.00E+04
2	8.00E+06	7.25E+00	6.81E-03	0.00E+00	1.70E+06	8.24E+03	7.33E+03	1.08E+04	8.00E+03	1.15E+04	1.14E+04
3	6.50E+06	5.75E+00	5.72E-03	0.00E+00	0.00E+00	1.70E+06	8.65E+03	1.21E+04	9.01E+03	1.30E+04	1.29E+04
4	5.00E+06	4.50E+00	4.79E-03	0.00E+00	0.00E+00	0.00E+00	1.69E+06	1.37E+04	9.99E+03	1.44E+04	1.43E+04
5	4.00E+06	3.50E+00	4.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.69E+06	1.08E+04	1.56E+04	1.56E+04
6	3.00E+06	2.75E+00	3.39E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.69E+06	1.58E+04	1.64E+04
7	2.50E+06	2.25E+00	2.93E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.68E+06	1.59E+04
8	2.00E+06	1.83E+00	2.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.68E+06
9	1.66E+06	1.50E+00	2.17E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	1.33E+06	1.17E+00	1.78E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	1.00E+06	9.00E-01	1.44E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	8.00E+05	7.00E-01	1.16E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	6.00E+05	5.00E-01	8.52E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	4.00E+05	3.50E-01	6.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	3.00E+05	2.50E-01	4.27E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.00E+05	1.50E-01	2.48E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	1.00E+05	7.50E-02	1.40E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	5.00E+04	3.00E-02	8.82E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	1.00E+04										

1 eV = 10^{-6} MeV

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.1.1.xls*. The receptor is assumed to be 1 m above the base of the drift facing in the direction normal to the drift cross-section. The most appropriate Fluence-to-Dose Factors for this calculation are those for the anterior-posterior and posterior-anterior (AP-PA) exposure geometry, since the gamma-rays are incident on the receptor primarily from the front and back. The values are linked to the **AP-PA** sheet in *ANSI-ANS-6.1.1.xls*, and the 1x18 array is named AP_PA_Dose_Factors. The first 8 energy groups of the Fluence Summary are presented on this page; the remaining 10 groups are presented on the following page. The Fluence Summary was created by cutting the values for the Total Flux, Node 29, from the Emplacement Drift Ground SCALE output (SURF_ED1.OUT and SURF_ED2.OUT) for each energy group and pasting them into this sheet. The resulting 18x18 array is named Empl_Drift_Fluence.

Surface Fluence-to-Dose Calculations for Emplacement Drift Geometry (Continued)

Fluence Summary: Output from 18-Group SCALE Calculation
Empl. Drift Surface, Radius = 255 cm, Receptor 1m Above Surface (Node 24) - Groups 9-18

Group 9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	Empl. Drift Dose mrem/hr
1.45E+04	2.40E+04	2.44E+04	4.16E+04	4.44E+05	1.76E+05	3.11E+05	7.47E+05	2.93E+05	3.36E+03	1.50E+04
1.65E+04	2.75E+04	2.81E+04	4.80E+04	3.86E+05	1.73E+05	3.04E+05	7.11E+05	2.78E+05	3.19E+03	1.27E+04
1.86E+04	3.11E+04	3.19E+04	5.48E+04	3.37E+05	1.73E+05	3.05E+05	6.91E+05	2.71E+05	3.10E+03	1.08E+04
2.06E+04	3.46E+04	3.57E+04	6.17E+04	2.93E+05	1.76E+05	3.14E+05	6.83E+05	2.67E+05	3.07E+03	9.21E+03
2.26E+04	3.79E+04	3.91E+04	6.82E+04	2.52E+05	1.82E+05	3.30E+05	6.87E+05	2.68E+05	3.08E+03	7.84E+03
2.40E+04	4.04E+04	4.17E+04	7.35E+04	2.22E+05	1.88E+05	3.53E+05	7.04E+05	2.75E+05	3.16E+03	6.73E+03
2.43E+04	4.18E+04	4.35E+04	7.69E+04	2.04E+05	1.94E+05	3.81E+05	7.32E+05	2.85E+05	3.28E+03	5.93E+03
2.32E+04	4.25E+04	4.46E+04	7.93E+04	1.92E+05	2.00E+05	4.16E+05	7.71E+05	2.99E+05	3.44E+03	5.21E+03
1.68E+06	4.03E+04	4.46E+04	8.00E+04	1.85E+05	2.05E+05	4.56E+05	8.17E+05	3.16E+05	3.64E+03	4.58E+03
0.00E+00	1.68E+06	4.11E+04	7.91E+04	1.81E+05	2.07E+05	5.12E+05	8.84E+05	3.41E+05	3.93E+03	3.91E+03
0.00E+00	0.00E+00	1.67E+06	7.14E+04	1.78E+05	2.04E+05	5.62E+05	9.67E+05	3.70E+05	4.27E+03	3.29E+03
0.00E+00	0.00E+00	0.00E+00	1.68E+06	1.64E+05	1.96E+05	5.49E+05	1.09E+06	4.07E+05	4.70E+03	2.76E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.71E+06	1.75E+05	4.91E+05	1.29E+06	4.64E+05	5.38E+03	2.16E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.69E+06	3.96E+05	1.52E+06	5.34E+05	6.21E+03	1.64E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.79E+06	1.70E+06	6.10E+05	7.12E+03	1.27E+03
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.80E+06	9.29E+05	1.11E+04	8.26E+02
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.62E+06	3.75E+04	3.71E+02
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.37E+06	1.21E+02

The highlighted1x18 array is named Empl_Drift_Dose; it is the product of a matrix multiplication operation between the 18x18 Empl_Drift_Fluence array and the 1x18 AP_PA_Dose_Factors array. The underlying formula for Empl_Drift_Dose is:

=MMULT(Main_Drift_Fluence,AP_PA_Dose_Factors)

The arguments of the MMULT function are described on the previous page. See Excel Help for more information on the MMULT function.

Surface Plane Geometry Factor Calculation for Main Drift and Emplacement Drift

Gamma-Ray Energy (E)			Inf. Plane	Main Drift	Empl. Drift	Main Drift	Empl. Drift
Energy Group	Upper (eV)	Mean (MeV)	Dose mrem/hr	Dose mrem/hr	Dose mrem/hr	Geometry Factor	Geometry Factor
1	1.00E+07	9.00E+00	1.88E+04	1.61E+04	1.50E+04	8.57E-01	7.99E-01
2	8.00E+06	7.25E+00	1.56E+04	1.37E+04	1.27E+04	8.74E-01	8.15E-01
3	6.50E+06	5.75E+00	1.31E+04	1.16E+04	1.08E+04	8.90E-01	8.30E-01
4	5.00E+06	4.50E+00	1.09E+04	9.88E+03	9.21E+03	9.08E-01	8.46E-01
5	4.00E+06	3.50E+00	9.09E+03	8.41E+03	7.84E+03	9.26E-01	8.63E-01
6	3.00E+06	2.75E+00	7.63E+03	7.22E+03	6.73E+03	9.46E-01	8.82E-01
7	2.50E+06	2.25E+00	6.59E+03	6.37E+03	5.93E+03	9.66E-01	9.00E-01
8	2.00E+06	1.83E+00	5.64E+03	5.59E+03	5.21E+03	9.90E-01	9.24E-01
9	1.66E+06	1.50E+00	4.82E+03	4.91E+03	4.58E+03	1.02E+00	9.50E-01
10	1.33E+06	1.17E+00	3.94E+03	4.18E+03	3.91E+03	1.06E+00	9.90E-01
11	1.00E+06	9.00E-01	3.16E+03	3.52E+03	3.29E+03	1.11E+00	1.04E+00
12	8.00E+05	7.00E-01	2.53E+03	2.94E+03	2.76E+03	1.16E+00	1.09E+00
13	6.00E+05	5.00E-01	1.84E+03	2.29E+03	2.16E+03	1.24E+00	1.17E+00
14	4.00E+05	3.50E-01	1.30E+03	1.74E+03	1.64E+03	1.34E+00	1.26E+00
15	3.00E+05	2.50E-01	9.42E+02	1.34E+03	1.27E+03	1.42E+00	1.35E+00
16	2.00E+05	1.50E-01	5.77E+02	8.68E+02	8.26E+02	1.51E+00	1.43E+00
17	1.00E+05	7.50E-02	2.74E+02	3.91E+02	3.71E+02	1.43E+00	1.35E+00
18	5.00E+04	3.00E-02	6.89E+01	1.22E+02	1.21E+02	1.78E+00	1.75E+00
	1.00E+04						

1 eV = 10^{-6} MeV

The gamma-ray energy table corresponds to the energy bounds defined in the 18-group SCALE calculation. The values are linked to the **Energy Groups** sheet in *ANSI-ANS-6.11.xls*. The three dose columns are copies of the results from the **Fluence-to-Dose** sheet of this workbook and are 1x18 arrays named Inf_Plane_Dose, Main_Drift_Dose, and Empl_Drift_Dose.

The first highlighted 1x18 array is the geometry factor for the Main Drift and is named Main_Drift_GF. The underlying formula for Main_Drift_GF is:

=Main_Drift_Dose/Inf_Plane_Dose

The second highlighted 1x18 array is the geometry factor for the Emplacement Drift and is named Empl_Drift_GF. The underlying formula for Empl_Drift_GF is:

=Empl_Drift_Dose/Inf_Plane_Dose

Sensitivity of Surface Contamination Dose Geometry Factors to Assumed Exposure Geometry

Energy Group	Emplacement Drift Exposure Geometry AP-PA	AP	Difference: (AP-APPA) / APPA
1	7.99E-01	8.12E-01	1.7%
2	8.15E-01	8.32E-01	2.1%
3	8.30E-01	8.50E-01	2.4%
4	8.46E-01	8.68E-01	2.7%
5	8.63E-01	8.88E-01	2.9%
6	8.82E-01	9.10E-01	3.2%
7	9.00E-01	9.32E-01	3.5%
8	9.24E-01	9.60E-01	3.9%
9	9.50E-01	9.93E-01	4.5%
10	9.90E-01	1.04E+00	5.2%
11	1.04E+00	1.10E+00	6.1%
12	1.09E+00	1.17E+00	7.0%
13	1.17E+00	1.26E+00	8.1%
14	1.26E+00	1.38E+00	9.1%
15	1.35E+00	1.48E+00	9.7%
16	1.43E+00	1.58E+00	10.0%
17	1.35E+00	1.56E+00	15.5%
18	1.75E+00	2.29E+00	30.7%

Energy Group	Main Drift Exposure Geometry AP-PA	AP	Difference: (AP-APPA) / APPA
1	8.57E-01	8.71E-01	1.6%
2	8.74E-01	8.92E-01	2.1%
3	8.90E-01	9.12E-01	2.4%
4	9.08E-01	9.32E-01	2.7%
5	9.26E-01	9.52E-01	2.9%
6	9.46E-01	9.76E-01	3.2%
7	9.66E-01	1.00E+00	3.5%
8	9.90E-01	1.03E+00	3.9%
9	1.02E+00	1.06E+00	4.4%
10	1.06E+00	1.11E+00	5.2%
11	1.11E+00	1.18E+00	6.1%
12	1.16E+00	1.25E+00	7.0%
13	1.24E+00	1.34E+00	8.1%
14	1.34E+00	1.46E+00	9.1%
15	1.42E+00	1.56E+00	9.7%
16	1.51E+00	1.66E+00	10.0%
17	1.43E+00	1.65E+00	15.5%
18	1.78E+00	2.32E+00	30.7%

Energy Group	Emplacement Drift Exposure Geometry AP-PA	LAT	Difference: (LAT-APPA) / APPA
1	7.99E-01	7.10E-01	-11.1%
2	8.15E-01	7.16E-01	-12.1%
3	8.30E-01	7.18E-01	-13.4%
4	8.46E-01	7.18E-01	-15.1%
5	8.63E-01	7.16E-01	-17.0%
6	8.82E-01	7.13E-01	-19.1%
7	9.00E-01	7.12E-01	-20.9%
8	9.24E-01	7.12E-01	-22.9%
9	9.50E-01	7.13E-01	-25.0%
10	9.90E-01	7.18E-01	-27.6%
11	1.04E+00	7.27E-01	-30.2%
12	1.09E+00	7.37E-01	-32.6%
13	1.17E+00	7.53E-01	-35.6%
14	1.26E+00	7.75E-01	-38.5%
15	1.35E+00	8.01E-01	-40.8%
16	1.43E+00	8.14E-01	-43.2%
17	1.35E+00	7.09E-01	-47.6%
18	1.75E+00	6.22E-01	-64.5%

Energy Group	Main Drift Exposure Geometry AP-PA	LAT	Difference: (LAT-APPA) / APPA
1	8.57E-01	7.61E-01	-11.1%
2	8.74E-01	7.68E-01	-12.1%
3	8.90E-01	7.71E-01	-13.4%
4	9.08E-01	7.71E-01	-15.1%
5	9.26E-01	7.68E-01	-17.0%
6	9.46E-01	7.66E-01	-19.0%
7	9.66E-01	7.64E-01	-20.9%
8	9.90E-01	7.63E-01	-22.9%
9	1.02E+00	7.64E-01	-24.9%
10	1.06E+00	7.68E-01	-27.5%
11	1.11E+00	7.76E-01	-30.1%
12	1.16E+00	7.86E-01	-32.5%
13	1.24E+00	8.01E-01	-35.6%
14	1.34E+00	8.21E-01	-38.5%
15	1.42E+00	8.45E-01	-40.7%
16	1.51E+00	8.56E-01	-43.2%
17	1.43E+00	7.48E-01	-47.6%
18	1.78E+00	6.30E-01	-64.5%

A sensitivity analysis is performed to assess the impact of the exposure geometry used for exposures in drifts. The Geometry Factors (GFs) for main and emplacement drifts are calculated using the anterior-posterior (AP, top tables) and lateral (LAT, bottom tables) exposure geometries. The underlying equations use the MMULT function, as shown in the **Fluence-to-Dose** sheet, to obtain the drift dose; this is divided by the infinite plane dose to obtain the GF. The results are then compared by calculating the percent difference from the GFs based on the AP-PA exposure geometry. This difference, as expected, is greatest at the lowest energy levels, and ranges from about 31 percent higher (AP) to about 65 percent lower (LAT).

Comparison of Results Using ANSI/ANS-6.1.1-1991 vs ANSI/ANS-6.1.1-1977

Energy Group	Semi-Infinite Slab ANSI/ANS-6.1.1 1991	1977	Difference
1	1.88E+04	2.22E+04	18.2%
2	1.56E+04	1.90E+04	21.5%
3	1.31E+04	1.63E+04	24.7%
4	1.09E+04	1.39E+04	27.6%
5	9.09E+03	1.19E+04	31.0%
6	7.63E+03	1.02E+04	33.9%
7	6.59E+03	8.98E+03	36.3%
8	5.64E+03	7.85E+03	39.1%
9	4.82E+03	6.86E+03	42.3%
10	3.94E+03	5.80E+03	47.2%
11	3.16E+03	4.86E+03	53.5%
12	2.53E+03	4.07E+03	61.0%
13	1.84E+03	3.13E+03	69.8%
14	1.30E+03	2.41E+03	85.6%
15	9.42E+02	1.81E+03	92.1%
16	5.77E+02	1.17E+03	103.6%
17	2.74E+02	7.22E+02	163.5%
18	6.89E+01	6.82E+02	889.7%

Energy Group	Main Drift ANSI/ANS-6.1.1 1991	1977	Difference
1	1.61E+04	1.78E+04	10.7%
2	1.37E+04	1.53E+04	12.3%
3	1.16E+04	1.33E+04	14.1%
4	9.88E+03	1.15E+04	15.9%
5	8.41E+03	9.96E+03	18.4%
6	7.22E+03	8.69E+03	20.4%
7	6.37E+03	7.77E+03	22.0%
8	5.59E+03	6.92E+03	23.9%
9	4.91E+03	6.18E+03	25.9%
10	4.18E+03	5.38E+03	28.9%
11	3.52E+03	4.66E+03	32.6%
12	2.94E+03	4.03E+03	36.8%
13	2.29E+03	3.23E+03	41.1%
14	1.74E+03	2.59E+03	49.5%
15	1.34E+03	2.04E+03	52.1%
16	8.68E+02	1.38E+03	58.6%
17	3.91E+02	7.38E+02	89.0%
18	1.22E+02	8.08E+02	559.8%

Energy Group	Emplacement Drift ANSI/ANS-6.1.1 1991	1977	Difference
1	1.50E+04	1.66E+04	10.7%
2	1.27E+04	1.43E+04	12.3%
3	1.08E+04	1.24E+04	14.2%
4	9.21E+03	1.07E+04	16.0%
5	7.84E+03	9.28E+03	18.4%
6	6.73E+03	8.11E+03	20.5%
7	5.93E+03	7.25E+03	22.1%
8	5.21E+03	6.46E+03	23.9%
9	4.58E+03	5.78E+03	26.0%
10	3.91E+03	5.04E+03	29.0%
11	3.29E+03	4.37E+03	32.7%
12	2.76E+03	3.78E+03	36.9%
13	2.16E+03	3.05E+03	41.2%
14	1.64E+03	2.45E+03	49.6%
15	1.27E+03	1.94E+03	52.2%
16	8.26E+02	1.31E+03	58.6%
17	3.71E+02	6.99E+02	88.7%
18	1.21E+02	7.98E+02	559.8%

A comparison was made to investigate the differences in dose obtained by using 1991 vs.1977 dose-to-fluence factors from ANSI/ANS-6.1.1. The first table compares the Inf_Plane_Dose array from the **Fluence-to-Dose** sheet with the Inf_Plane_Fluence converted to dose using the 1977 fluence-to dose factors (Old_Dose_Factors) from the **1977 Factors** sheet of the *ANSI-ANS-6.1.1.xls* workbook. The resulting array is named Inf_Plane_Dose_77, with an underlying formula of:

=MMULT(Inf_Plane_Fluence,'ANSI-ANS-6.1.1.xls'!Old_Dose_Factors)

The last column in the table is the percent difference between the 1991 and 1977 values.

The other two tables perform similar calculations targeted to main and emplacement drift dose factors, respectively.

The greatest differences are found at the lower gamma-ray energy groups, because this is where the 1991 and 1977 versions of ANSI/ANS-6.1.1 fluence-to-dose factors exhibit the greatest deviation. As expected, the differences by energy group are the about the same in the main and emplacement drift comparisons due to the use of the AP-PA exposure geometry in both cases. However, the differences in the infinite plane comparison are significantly greater. This is because the ROT exposure geometry dose-to-fluence factors are lower than the AP-PA factors, which in turn are lower than the 1977 factors.

C.4 ANSI-ANS-6.1.1.xls: Gamma-Ray Fluence-to-Dose Factors

1. Purpose

The purpose of this workbook, *ANSI-ANS-6.1.1.xls*, is to provide gamma-ray fluence-to-dose factors using the coefficients and methodology provided in ANSI/ANS-6.1.1-1991, *Neutron and Gamma-Ray Fluence-to-Dose Factors*. These fluence-to-dose factors allow the calculation of effective dose equivalent rates from the gamma-ray fluence that is an output of gamma and neutron transport codes. A comparison is also made with the 1977 version of the same standard.

2. Organization and Function

There are 12 sheets (including this Introduction) within this workbook. The right-hand header identifies the name of the sheet. The function and calculations performed by each sheet, as well as any input and output values or links, are summarized in the following sections. The variable names that have been assigned to each sheet are identified. These are used to simplify the calculation formulas used in this workbook. The formulas themselves are described in each sheet. Color coding, shading, and text boxes are used throughout this workbook to report the calculations performed and identify the names and ranges of input and output cells.

2.1 Introduction

This sheet.

2.2 Coefficients

This sheet tabulates the polynomial coefficients from ANSI/ANS-6.1.1-1991, Table 5, by Exposure Geometry and Gamma-Ray Energy Bounds. These coefficients are used as inputs to the following sheets: AP, PA, LAT, ROT, ISO. This sheet has no other inputs and does not perform calculations.

2.3 Energy Groups

This sheet tabulates the energy groups used in the derivation of the fluence-to-dose factors. Up to 18 groups may be entered and are listed in the first column. The upper bound of each energy group (in eV) is tabulated in the second column. This is the primary input; the energies entered here must match the bounding energies used in the code that generates the fluence values. The mean energy (converted from eV to Mev) in each group is calculated based on the average between the upper bound for that group and the upper bound for the next group. An additional single photon energy may be entered in MeV.

2.4 AP

This is the calculation sheet for Anterior-Posterior exposure geometry. The fluence-to-dose factors generated as output from this sheet apply to conditions when the gamma rays are primarily incident on the front of the individual. These factors also apply to conditions where the exposure geometry is unknown. The first column lists the energy group numbers for which each fluence-to-dose factor applies. The second column presents the calculated fluence-to-dose factors (in Sv-cm^2) based on the polynomial equation (Equation 9 of ANSI/ANS-6.1.1-1991). The inputs are the ln (mean energy) from the Energy Groups sheet and the coefficients for AP exposure geometry and energy bounds from the Coefficients sheet. The third column converts the values in the second column to units of mrem/hr per gamma/cm^2-sec. The array of results in this column is named AP_Dose_Factors.

2.5 PA

This is the calculation sheet for Posterior-Anterior exposure geometry. The fluence-to-dose factors generated as output from this sheet apply to conditions when the gamma rays are primarily incident on the rear of the individual. The inputs and outputs are similar to those for the AP sheet. The array of results in the third column is named PA_Dose_Factors.

2.6 AP-PA

This is the calculation sheet for a combination of Anterior-Posterior and Posterior Anterior exposure geometries. The fluence-to-dose factors generated as output from this sheet apply to conditions when the gamma rays are primarily incident on the front AND rear of the individual. The inputs are the fluence-to-dose factors calculated in the AP and PA sheets. The sheet calculates the average of these input values for each energy group. The outputs are similar to those for the AP sheet. The array of results in the third column is named AP_PA_Dose_Factors.

2.7 LAT

This is the calculation sheet for Lateral exposure geometry. The fluence-to-dose factors generated as output from this sheet apply to conditions when the gamma rays are primarily incident on the side(s) of the individual. The inputs and outputs are similar to those for the AP sheet. The array of results in the third column is named LAT_Dose_Factors.

2.8 ROT

This is the calculation sheet for Rotational exposure geometry. The fluence-to-dose factors generated as output from this sheet apply to conditions when the gamma rays are primarily incident on the front, rear and side(s) of the individual. The inputs and outputs are similar to those for the AP sheet. The array of results in the third column is named ROT_Dose_Factors.

2.9 ISO

This is the calculation sheet for Isotropic exposure geometry. The fluence-to-dose factors generated as output from this sheet apply to conditions when the gamma rays are incident on the front, rear, top, bottom and side(s) of the individual. The inputs and outputs are similar to those for the AP sheet. The array of results in the third column is named ISO_Dose_Factors.

2.10 1977 Factors

This is the calculation sheet for the ANSI/ANS-6.1.1-1977 standard. The fluence-to-dose factors generated as output from this sheet is based on ambient (or "deep") dose equivalent conditions. The third column presents the calculated fluence-to-dose factors (converted to mrem/hr per photon/cm^2-sec) based on the polynomial equation (Table 4 of ANSI/ ANS-6.1.1-1977) . The inputs are the average energy from the Energy Groups sheet. The array of results in the third column is named Old_Dose_Factors.

2.11 Verification Check

This sheet performs a verification check to determine whether the polynomial expression for the fluence-to-dose factors was implemented correctly. The inputs are fluence-to-dose factors for two gamma-ray energy groups generated by the AP through ISO sheets. The sheet calculates percent differences from the Table 3 values in ANSI/ANS-6.1.1-1991 for these two gamma-ray energies.

2.12 Comparison

This sheet displays a plot of the fluence-to-dose factors as a function of gamma-ray energy for the six exposure geometries based on ANSI/ANS-6.1.1-1991 plus the fluence-to-dose factors from ANSI/ANS-6.1.1-1977. It allows a quick comparison of the values calculated by this workbook and graphically displays the significant differences, especially at lower gamma-ray energies, between the 1977 and 1991 standards.

3. Results and Conclusions

Based on the results of the Verification Check sheet, there is reasonable assurance that Equation 9 of ANSI/ANS-6.1.1-1991 has been implemented correctly in this spreadsheet.

4. Workbook Links

There are no links from other workbooks into this workbook. Results from this workbook are used in the following workbooks: *Surface DCF.xls*, *Submersion DCF.xls*, and *Radionuclide DCF.xls*.

The following named ranges in this workbook are used in those links: Group_Number, Upper_Energy, Mean_Energy, AP_Dose_Factors, AP_PA_Dose_Factors, ISO_Dose_Factors, LAT_Dose_Factors, ROT_Dose_Factors, and Old_Dose_Factors.

Author: E. R. Faillace - last modified 8/22/2000

Polynomial Coefficients in the Analytical Fit of $h_E(E)$ for Gamma Rays*
Source: ANSI/ANS-6.1.1-1991 - Table 5

Gamma-Ray Energy Bounds	Coefficients C_0	C_1	C_2	C_3	C_4
AP Exposure**					
E<0.15 MeV	2.30402	0.75167	-1.04725	-0.50091	-0.06302
E>0.15 MeV	1.52070	0.79329	-0.07261	0.01228	0.00347
PA Exposure					
E<0.015 MeV	56.09000	14.17975	0.0	0.0	0.0
0.015<E< 0.1 MeV	-4.27492	-9.52586	-7.06215	-2.02976	-0.20889
E>0.10 MeV	1.42685	0.86211	-0.09311	0.00402	0.00800
LAT Exposure					
E<0.15 MeV	13.31850	18.22077	8.61214	1.82597	0.13867
E>0.15 MeV	1.17185	0.96410	-0.09305	0.00211	0.00650
ROT Exposure					
E<0.15 MeV	5.15939	5.13418	1.21881	0.02805	-0.01816
E>0.15 MeV	1.32196	0.87836	-0.09933	0.00517	0.00908
ISO Exposure					
E<0.10 MeV	1.22920	0.0	-1.37145	-0.53901	-0.06363
E>0.10 MeV	1.18229	0.92497	-0.09282	0.00305	0.00772

Variable Namelist

Gamma-Ray Energy Bounds	Coefficients C_0	C_1	C_2	C_3	C_4
AP Exposure**					
E<0.15 MeV	AP1_C0	AP1_C1	AP1_C2	AP1_C3	AP1_C4
E>0.15 MeV	AP2_C0	AP2_C1	AP2_C2	AP2_C3	AP2_C4
PA Exposure					
E<0.015 MeV	PA1_C0	PA1_C1	PA1_C2	PA1_C3	PA1_C4
0.015<E< 0.1 MeV	PA2_C0	PA2_C1	PA2_C2	PA2_C3	PA2_C4
E>0.10 MeV	PA3_C0	PA3_C1	PA3_C2	PA3_C3	PA3_C4
LAT Exposure					
E<0.15 MeV	LAT1_C0	LAT1_C1	LAT1_C2	LAT1_C3	LAT1_C4
E>0.15 MeV	LAT2_C0	LAT2_C1	LAT2_C2	LAT2_C3	LAT2_C4
ROT Exposure					
E<0.15 MeV	ROT1_C0	ROT1_C1	ROT1_C2	ROT1_C3	ROT1_C4
E>0.15 MeV	ROT2_C0	ROT2_C1	ROT2_C2	ROT2_C3	ROT2_C4
ISO Exposure					
E<0.10 MeV	ISO1_C0	ISO1_C1	ISO1_C2	ISO1_C3	ISO1_C4
E>0.10 MeV	ISO2_C0	ISO2_C1	ISO2_C2	ISO2_C3	ISO2_C4

*Polynomial coefficients in analytic fit:
$h_E(E) = 10^{-12} \times \exp(C_0 + C_1X + C_2X^2 + C_3X^3 + C_4X^4)$ Sv-cm^2,
E = energy (MeV) and X = ln(E).

**If the orientation of the receptor with respect to the radiation field is unknown, AP exposure geometry values should be used.

Energy Group Calculation

Enter the upper energy (in eV) for each group in the shaded area:

Gamma-Ray Energy (E)			
Group	Upper (eV)	Mean (MeV)	ln(mean E)
1	1.00E+07	9.00E+00	2.1972
2	8.00E+06	7.25E+00	1.9810
3	6.50E+06	5.75E+00	1.7492
4	5.00E+06	4.50E+00	1.5041
5	4.00E+06	3.50E+00	1.2528
6	3.00E+06	2.75E+00	1.0116
7	2.50E+06	2.25E+00	0.8109
8	2.00E+06	1.83E+00	0.6043
9	1.66E+06	1.50E+00	0.4021
10	1.33E+06	1.17E+00	0.1527
11	1.00E+06	9.00E-01	-0.1054
12	8.00E+05	7.00E-01	-0.3567
13	6.00E+05	5.00E-01	-0.6931
14	4.00E+05	3.50E-01	-1.0498
15	3.00E+05	2.50E-01	-1.3863
16	2.00E+05	1.50E-01	-1.8971
17	1.00E+05	7.50E-02	-2.5903
18	5.00E+04	3.00E-02	-3.5066
	1.00E+04	MeV	ln(mean E)
Gamma-ray energy:		1.33E+00	0.2852

Variable Namelist

Mean (MeV)	ln(mean E)
eg_1	X_1
eg_2	X_2
eg_3	X_3
eg_4	X_4
eg_5	X_5
eg_6	X_6
eg_7	X_7
eg_8	X_8
eg_9	X_9
eg_10	X_10
eg_11	X_11
eg_12	X_12
eg_13	X_13
eg_14	X_14
eg_15	X_15
eg_16	X_16
eg_17	X_17
eg_18	X_18
E	X

1 eV = 10^{-6} MeV

The underlying formula is:

=LN(eg_1)

where eg_1 is the mean energy for the 1st energy group. For the other cells in this column, the formula is LN(eg_*i*), where *i* is the group number.

This cell entry allows the entry of a single gamma-ray energy that is different from the mean energy of the 18 groups specified above.

Anterior-Posterior Exposure Geometry

Energy Group	Fluence-to-Dose Factor 10^{-12} Sv-cm^2	Fluence-to-Dose Factor mrem/hr per γ/cm^2-sec
1	22.7447	8.19E-03
2	19.2242	6.92E-03
3	16.1896	5.83E-03
4	13.5875	4.89E-03
5	11.3957	4.10E-03
6	9.6334	3.47E-03
7	8.3671	3.01E-03
8	7.2193	2.60E-03
9	6.2267	2.24E-03
10	5.1562	1.86E-03
11	4.2051	1.51E-03
12	3.4144	1.23E-03
13	2.5413	9.15E-04
14	1.8182	6.55E-04
15	1.2989	4.68E-04
16	0.7503	2.70E-04
17	0.4489	1.62E-04
18	0.3201	1.15E-04

To convert from 10^{-12} Sv-cm^2 to mrem/hr per γ/cm^2-sec:

1 Sv = 100 rem = 10^5 mrem

10^{-12} Sv-cm^2 = 10^{-7} mrem-cm^2 x 3600 sec/hr

= 3.6 x 10^{-4} mrem/hr per γ/cm^2-sec

For photon energy of: 1.33 MeV
Fluence-to-Dose is: 5.7049 10^{-12} Sv-cm^2 or
2.05E-03 mrem/hr per γ/cm^2-s

Do not overwrite! Value previously entered in **Energy Groups** sheet.

The underlying formula is:

=IF(eg_1<=0.15,
is true, then use EXP(AP1_C0+AP1_C1*X_1+AP1_C2*X_1^2+AP1_C3*X_1^3+AP1_C4*X_1^4),
otherwise, use EXP(AP2_C0+AP2_C1*X_1+AP2_C2*X_1^2+AP2_C3*X_1^3+AP2_C4*X_1^4))

For other energy groups, subsitute eg_*i* for eg_1, and X_*i* for X_1, where *i* represents the energy group number. See the **Energy Groups** sheet for the underlying values of these variables. See the **Coefficients** sheet for the values of the polynomial coefficients AP*x* _C*x* .

The next column converts the calculated value to conventional units using the formula shown above. The resulting array is named AP_Dose_Factors.

Posterior Anterior Exposure Geometry

Energy Group	Fluence-to-Dose Factor 10^{-12} Sv-cm^2	Fluence-to-Dose Factor mrem/hr per γ/cm^2-sec
1	22.2132	8.00E-03
2	18.6110	6.70E-03
3	15.5860	5.61E-03
4	13.0334	4.69E-03
5	10.8955	3.92E-03
6	9.1726	3.30E-03
7	7.9275	2.85E-03
8	6.7923	2.45E-03
9	5.8063	2.09E-03
10	4.7415	1.71E-03
11	3.7999	1.37E-03
12	3.0267	1.09E-03
13	2.1925	7.89E-04
14	1.5284	5.50E-04
15	1.0742	3.87E-04
16	0.6265	2.26E-04
17	0.3291	1.18E-04
18	0.1697	6.11E-05

To convert from 10^{-12} Sv-cm^2 to mrem/hr per γ/cm^2-sec:

1 Sv = 100 rem = 10^5 mrem

10^{-12} Sv-cm^2 = 10^{-7} mrem-cm^2 x 3600 sec/hr

= 3.6 x 10^{-4} mrem/hr per γ/cm^2-sec

For photon energy of: 1.33 MeV
Fluence-to-Dose is: 5.2872 10^{-12} Sv-cm^2 or
1.90E-03 mrem/hr per γ/cm^2-s

Do not overwrite! Value previously entered in **Energy Groups** sheet.

The underlying formula is:

=IF(eg_1<=0.015,
is true, then use EXP(PA1_C0+PA1_C1*X_1+PA1_C2*X_1^2+PA1_C3*X_1^3+PA1_C4*X_1^4),
otherwise, IF(eg_1<=0.1,
is true, then use EXP(PA2_C0+PA2_C1*X_1+PA2_C2*X_1^2+PA2_C3*X_1^3+PA2_C4*X_1^4),
otherwise, use EXP(PA3_C0+PA3_C1*X_1+PA3_C2*X_1^2+PA3_C3*X_1^3+PA3_C4*X_1^4)))

For other energy groups, subsitute eg_*i* for eg_1, and X_*i* for X_1, where *i* represents the energy group number. See the **Energy Groups** sheet for the underlying values of these variables. See the **Coefficients** sheet for the values of the polynomial coefficients PA*x*_C*x*.

The next column converts the calculated value to conventional units using the formula shown above. The resulting array is named PA_Dose_Factors.

Average Anterior-Posterior and Posterior Anterior Exposure Geometry

Energy Group	Fluence-to-Dose Factor 10^{-12} Sv-cm^2	Fluence-to-Dose Factor mrem/hr per g/cm^2-sec
1	22.4789	8.09E-03
2	18.9176	6.81E-03
3	15.8878	5.72E-03
4	13.3104	4.79E-03
5	11.1456	4.01E-03
6	9.4030	3.39E-03
7	8.1473	2.93E-03
8	7.0058	2.52E-03
9	6.0165	2.17E-03
10	4.9489	1.78E-03
11	4.0025	1.44E-03
12	3.2206	1.16E-03
13	2.3669	8.52E-04
14	1.6733	6.02E-04
15	1.1866	4.27E-04
16	0.6884	2.48E-04
17	0.3890	1.40E-04
18	0.2449	8.82E-05

To convert from 10^{-12} Sv-cm^2 to mrem/hr per γ/cm^2-sec:

1 Sv = 100 rem = 10^5 mrem

10^{-12} Sv-cm^2 = 10^{-7} mrem-cm^2 x 3600 sec/hr

= **3.6 x 10^{-4} mrem/hr per γ/cm^2-sec**

For photon energy of: 1.33 MeV

Fluence-to-Dose is: 5.4960 10^{-12} Sv-cm^2 or

1.98E-03 mrem/hr per γ/cm^2-s

Do not overwrite! Value previously entered in **Energy Groups** sheet.

The underlying formula is:

=AVERAGE(AP!B6,PA!B6)

B6 is the cell reference for the first energy group Fluence-to-Dose Factor in the AP and PA sheets. For other energy groups, subsitute B*n*, where *n* =(5+*i*) and *i* is the energy group number, for B6.

The next column converts the calculated value to conventional units using the formula shown above. The resulting array is named AP_PA_Dose_Factors.

Lateral Exposure Geometry

Energy Group	Fluence-to-Dose Factor 10^{-12} Sv-cm^2	Fluence-to-Dose Factor mrem/hr per γ/cm^2-sec
1	20.3860	7.34E-03
2	16.9977	6.12E-03
3	14.0932	5.07E-03
4	11.6101	4.18E-03
5	9.5235	3.43E-03
6	7.8531	2.83E-03
7	6.6620	2.40E-03
8	5.5947	2.01E-03
9	4.6870	1.69E-03
10	3.7319	1.34E-03
11	2.9132	1.05E-03
12	2.2618	8.14E-04
13	1.5836	5.70E-04
14	1.0646	3.83E-04
15	0.7224	2.60E-04
16	0.3969	1.43E-04
17	0.2046	7.36E-05
18	0.0869	3.13E-05

To convert from 10^{-12} Sv-cm^2 to mrem/hr per γ/cm^2-sec:

1 Sv = 100 rem = 10^5 mrem

10^{-12} Sv-cm^2 = 10^{-7} mrem-cm^2 x 3600 sec/hr

= 3.6 x 10^{-4} mrem/hr per γ/cm^2-sec

For photon energy of: 1.33 MeV
Fluence-to-Dose is: 4.2178 10^{-12} Sv-cm^2 or
1.52E-03 mrem/hr per γ/cm^2-s

Do not overwrite! Value previously entered in **Energy Groups** sheet.

The underlying formula is:

=IF(eg_1<=0.15,
is true, then use
EXP(LAT1_C0+LAT1_C1*X_1+LAT1_C2*X_1^2+LAT1_C3*X_1^3+LAT1_C4*X_1^4),
otherwise, use
EXP(LAT2_C0+LAT2_C1*X_1+LAT2_C2*X_1^2+LAT2_C3*X_1^3+LAT2_C4*X_1^4))

For other energy groups, subsitute eg_*i* for eg_1, and X_*i* for X_1, where *i* represents the energy group number. See the **Energy Groups** sheet for the underlying values of these variables. See the **Coefficients** sheet for the values of the polynomial coefficients LAT*x*_C*x*.

The next column converts the calculated value to conventional units using the formula shown above. The resulting array is named LAT_Dose_Factors.

Rotational Exposure Geometry

Energy Group	Fluence-to-Dose Factor 10^{-12} Sv-cm^2	mrem/hr per γ/cm^2-sec
1	20.8811	7.52E-03
2	17.3261	6.24E-03
3	14.3988	5.18E-03
4	11.9704	4.31E-03
5	9.9640	3.59E-03
6	8.3622	3.01E-03
7	7.2110	2.60E-03
8	6.1647	2.22E-03
9	5.2576	1.89E-03
10	4.2794	1.54E-03
11	3.4154	1.23E-03
12	2.7073	9.75E-04
13	1.9460	7.01E-04
14	1.3437	4.84E-04
15	0.9353	3.37E-04
16	0.5374	1.93E-04
17	0.2817	1.01E-04
18	0.1632	5.88E-05

To convert from 10^{-12} Sv-cm^2 to mrem/hr per γ/cm^2-sec:

1 Sv = 100 rem = 10^5 mrem

10^{-12} Sv-cm^2 = 10^{-7} mrem-cm^2 x 3600 sec/hr

= **3.6×10^{-4} mrem/hr per γ/cm^2-sec**

For photon energy of: 1.33 MeV
Fluence-to-Dose is: 4.7805 10^{-12} Sv-cm^2 or
1.72E-03 mrem/hr per γ/cm^2-s

Do not overwrite! Value previously entered in **Energy Groups** sheet.

The underlying formula is:

=IF(eg_1<=0.15,
is true, then use
EXP(ROT1_C0+ROT1_C1*X_1+ROT1_C2*X_1^2+ROT1_C3*X_1^3+ROT1_C4*X_1^4),
otherwise, use
EXP(ROT2_C0+ROT2_C1*X_1+ROT2_C2*X_1^2+ROT2_C3*X_1^3+ROT2_C4*X_1^4))

For other energy groups, subsitute eg_*i* for eg_1, and X_*i* for X_1, where *i* represents the energy group number. See the **Energy Groups** sheet for the underlying values of these variables. See the **Coefficients** sheet for the values of the polynomial coefficients ROT*x*_C*x*.

The next column converts the calculated value to conventional units using the formula shown above. The resulting array is named ROT_Dose_Factors.

Isotropic Exposure Geometry

Energy Group	Fluence-to-Dose Factor 10^{-12} Sv-cm^2	Fluence-to-Dose Factor mrem/hr per γ/cm^2-sec
1	19.6648	7.08E-03
2	16.3300	5.88E-03
3	13.5291	4.87E-03
4	11.1721	4.02E-03
5	9.2110	3.32E-03
6	7.6465	2.75E-03
7	6.5293	2.35E-03
8	5.5238	1.99E-03
9	4.6629	1.68E-03
10	3.7487	1.35E-03
11	2.9559	1.06E-03
12	2.3177	8.34E-04
13	1.6443	5.92E-04
14	1.1216	4.04E-04
15	0.7726	2.78E-04
16	0.4271	1.54E-04
17	0.2301	8.28E-05
18	0.1334	4.80E-05

To convert from 10^{-12} Sv-cm^2 to mrem/hr per γ/cm^2-sec:

1 Sv = 100 rem = 10^5 mrem

10^{-12} Sv-cm^2 = 10^{-7} mrem-cm^2 x 3600 sec/hr

= **3.6 x 10^{-4} mrem/hr per γ/cm^2-sec**

For photon energy of: 1.33 MeV
Fluence-to-Dose is: 4.2150 10^{-12} Sv-cm^2 or
1.52E-03 mrem/hr per γ/cm^2-s

Do not overwrite! Value previously entered in **Energy Groups** sheet.

The underlying formula is:

=IF(eg_1<=0.15,
is true, then use EXP(ISO1_C0+ISO1_C1*X_1+ISO1_C2*X_1^2+ISO1_C3*X_1^3+ISO1_C4*X_1^4),
otherwise, use EXP(ISO2_C0+ISO2_C1*X_1+ISO2_C2*X_1^2+ISO2_C3*X_1^3+ISO2_C4*X_1^4))

For other energy groups, subsitute eg_*i* for eg_1, and X_*i* for X_1, where *i* represents the energy group number. See the **Energy Groups** sheet for the underlying values of these variables. See the **Coefficients** sheet for the values of the polynomial coefficients ISO*x*_C*x*.

The next column converts the calculated value to conventional units using the formula shown above. The resulting array is named ISO_Dose_Factors.

1977 Standard

Energy Group	Mean Energy MeV	Flux-to-Dose Factor mrem/hr per γ/cm^2-sec
1	9.00E+00	8.77E-03
2	7.25E+00	7.48E-03
3	5.75E+00	6.37E-03
4	4.50E+00	5.42E-03
5	3.50E+00	4.63E-03
6	2.75E+00	3.96E-03
7	2.25E+00	3.47E-03
8	1.83E+00	3.02E-03
9	1.50E+00	2.63E-03
10	1.17E+00	2.21E-03
11	9.00E-01	1.83E-03
12	7.00E-01	1.52E-03
13	5.00E-01	1.15E-03
14	3.50E-01	8.78E-04
15	2.50E-01	6.31E-04
16	1.50E-01	3.79E-04
17	7.50E-02	2.58E-04
18	3.00E-02	5.82E-04

For photon energy of: 1.33 MeV
Fluence-to-Dose is: 2.42E-03 mrem/hr per γ/cm^2-s

Do not overwrite! Value previously entered in **Energy Groups** sheet.

The underlying formula is:

=IF(eg_1<=0.5,
is true, then use EXP(-13.626+-0.57117*X_1+-1.0954*X_1^2+-0.24897*X_1^3),
otherwise, IF(eg_1<=5,
is true, then use EXP(-13.133+0.72008*X_1+-0.033603*X_1^2),
otherwise, use EXP(-12.791+0.28309*X_1+0.10873*X_1^2)))
multiply by *1000

For other energy groups, subsitute eg_*i* for eg_1, and X_*i* for X_1, where *i* represents the energy group number. See the **Energy Groups** sheet for the underlying values of these variables. The values of the coefficients of the polynomial expression are from Table 4 of ANSI/ANS-6.1.1-1977. A factor of 1000 is used to convert the result from units of rem to mrem. The resulting array is named Old_Dose_Factors.

Verification Check

A test was made to verify the correct application in this spreadsheet of the analytical representation (Equation 9 of ANSI/ANS-6.1.1 - 1991) of the fluence-to-dose factors. Section 6.1 of ANSI/ANS-6.1.1 states that "the gamma-ray fits generally reproduce the data to within a percent or better above 300 keV, gamma-ray energy. Below that energy the fits reproduce the data to within 5% or better." The fluence-to-dose factors for two mean gamma-ray energies, 1.5 MeV (Group 9) and 30 keV (Group 18), obtained with this spreadsheet were compared with the values in Table 3 of ANSI/ANS-6.1.1 - 1991. The comparison, along with the percent difference, is shown below. Values from the spreadsheet are rounded to 4 digits.

Gamma-Ray Energy = **1.5 MeV** (Group 9)

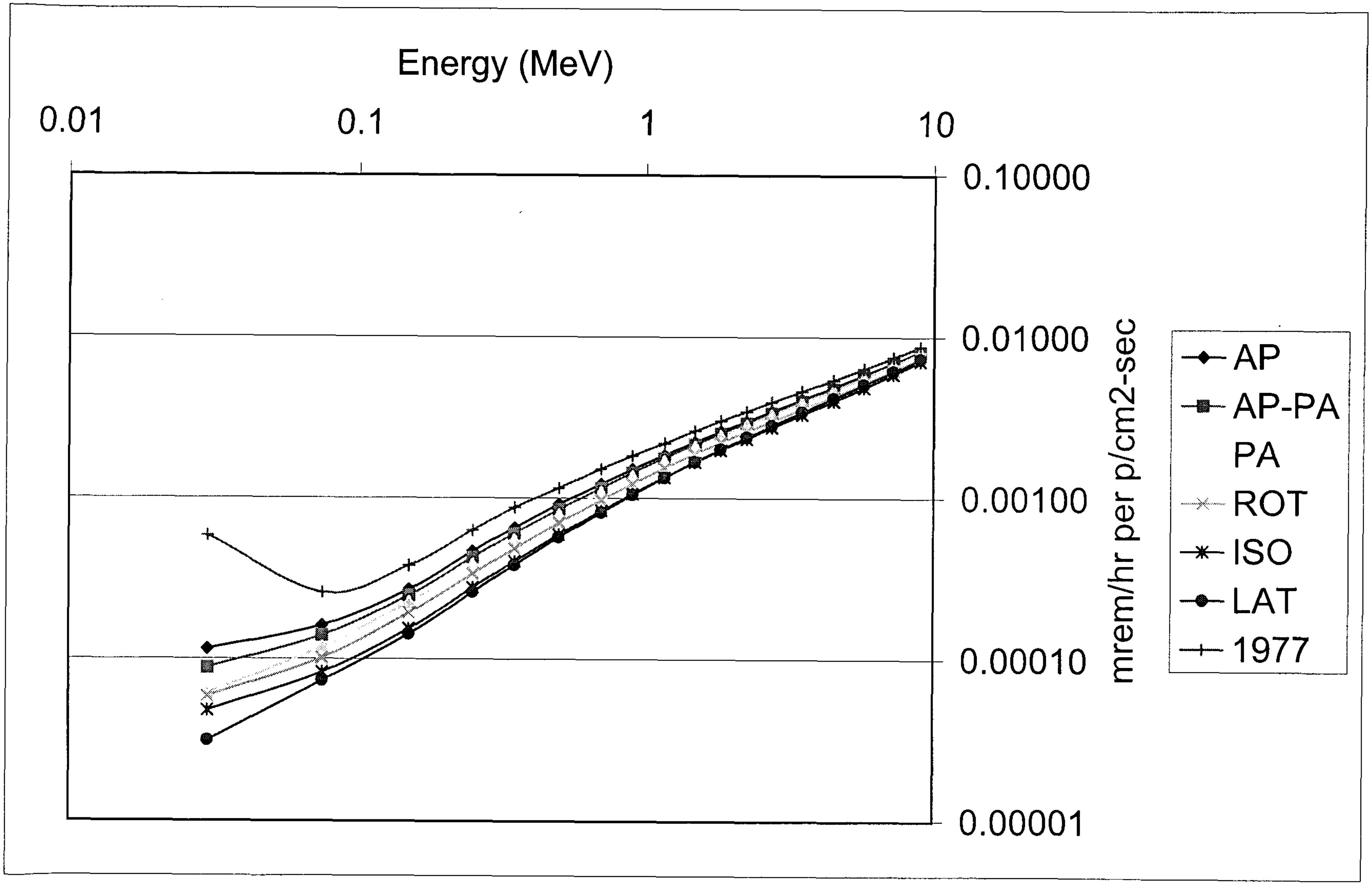
	Exposure Geometry				
	AP	PA	LAT	ROT	ISO
Spreadsheet	6.2267	5.8063	4.6870	5.2576	4.6629
Table 3	6.2400	5.8000	4.7000	5.2400	4.6800
Difference	-0.2%	0.1%	-0.3%	0.3%	-0.4%

Gamma-Ray Energy = **30 keV** (Group 18)

	Exposure Geometry				
	AP	PA	LAT	ROT	ISO
Spreadsheet	0.3201	0.1697	0.0869	0.1632	0.1334
Table 3	0.3290	0.1610	0.0863	0.1660	0.1380
Difference	-2.7%	5.4%	0.7%	-1.7%	-3.3%

The above results are consistent with the statements in Section 6.1 of ANSI/ANS-6.1.1 and match the graphical results presented in Figure 4 of ANSI/ANS-6.1.1. Therefore, there is reasonable assurance that Equation 9 of ANSI/ANS-6.1.1 has been implemented correctly in this spreadsheet.

Comparison of Fluence-to-Dose Factors for Each Exposure Geometry in ANSI/ANS-6.1.1-1991 and ANSI/ANS-6.1.1-1977



APPENDIX D

PROTECTION FACTORS FOR RESPIRATORS

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APPENDIX D - PROTECTION FACTORS FOR RESPIRATORS

The following table and associated footnotes has been reproduced from Appendix A to 10 CFR 20. It is included in this report to provide a quick reference for the selection and application of appropriate respiratory protection factors.

Appendix A to Part 20-Protection Factors for Respirators[a]						
Description[b]			Protection Factors[d]			Tested & Certified Equipment
			Modes[c]	Particulates only	Particulates, gases, & vapors[e]	National Institute for Occupational Safety and Health/Mine Safety and Health Administration tests for permissibility
I.	Air-Purifying Respirators:[f]					
	Facepiece, half-mask[g]		NP	10		30 CFR Part 11, Subpart K
	Facepiece, full		NP	50		
	Facepiece, half-mask full, or hood		PP	1000		
II.	Atmosphere-Supplying Respirators:					
	1.	Air-line respirator:				
		Facepiece, half-mask	CF		1000	30 CFR Part 11, Subpart J.
		Facepiece, half-mask	D		5	
		Facepiece, full	CF		2000	
		Facepiece, full	D		5	
		Facepiece, full	PD		2000	
		Hood	CF		([h])	
		Suit	CF		([i])	([j])
	2.	Self-contained breathing apparatus (SCBA):				
		Facepiece, full	D		50	30 CFR Part 11, Subpart H.
		Facepiece, full	PD		[k]10,000	
		Facepiece, full	RD		50	
		Facepiece, full	RP		[l]5,000	
III.	Combination Respirators:					
		Any combination of air-purifying and atmosphere-supplying respirators.			Protection factor for type and mode of operation as listed above.	30 CFR Part 11, §11.63(b).

Footnotes:

a. For use in the selection of respiratory protective devices to be used only where the contaminants have been identified and the concentrations (or possible concentrations) are known.

b. Only for shaven faces and where nothing interferes with the seal of tight-fitting facepieces against the skin. (Hoods and suits are excepted.)

c. The mode symbols are defined as follows:
CF=continuous flow
D=demand
NP=negative pressure (i.e., negative phase during inhalation)
PD=pressure demand (i.e., always positive pressure)
PP=positive pressure
RD=demand, recirculating (closed circuit)
RP=pressure demand, recirculating (closed circuit)

d. 1. The protection factor is a measure of the degree of protection afforded by a respirator, defined as the ratio of the concentration of airborne radioactive material outsid

e. e the respiratory protective equipment to that inside the equipment (usually inside the facepiece) under conditions of use. It is applied to the ambient airborne concentration to estimate the concentrations inhaled by the wearer according to the following formula:

$$\begin{pmatrix}\textbf{Concentration}\\\textbf{inhaled}\end{pmatrix} = \frac{\begin{pmatrix}\textbf{Ambient airborne}\\\textbf{concentration}\end{pmatrix}}{\begin{pmatrix}\textbf{Protection}\\\textbf{factor}\end{pmatrix}}$$

2. The protection factors apply:
(a) Only for individuals trained in using respirators and wearing properly fitted respirators that are used and maintained under supervision in a well-planned respiratory program.
(b) For air-purifying respirators only when high efficiency particulate filters (above 99.97% removal efficiency by thermally generated 0.3 μm dioctyl pthalate (DOP) test or equivalent) are used in atmospheres not deficient in oxygen and not containing radioactive gas or vapor respiratory hazards.
(c) No adjustment is to be made for the use of sorbents against radioactive material in the form of gases or vapors.
(d) For atmosphere-supplying respirators only when supplied with adequate respirable air. Respirable air shall be provided of the quality and quantity required in accordance with NIOSH/MSHA certification (described in 30 CFR part 11). Oxygen and air shall not be used in the same apparatus.

f. Excluding radioactive contaminants that present an absorption or submersion hazard. For tritium oxide, approximately one-third of the intake occurs by absorption through the skin so that an overall protection factor of less than 2 is appropriate when atmosphere-supplying respirators are used to protect against tritium oxide. If the protection factor for a device is 5 the effective protection factor for tritium is about 1.4; for devices with protection factors of 10 the effective factor tritium oxide is about 1.7, and for devices with protection factors of 100 or more the effective factor for tritium oxide is about 1.9. Air purifying respirators are not suitable for protection against tritium oxide. See also footnote *i* concerning supplied-air suits.

g. Canisters and cartridges shall not be used beyond service-life limitations.

h. Under-chin type only. This type of respirator is not satisfactory for use where it might be possible (e.g., if an accident or emergency were to occur) for the ambient airborne concentrations to reach instantaneous values greater than 10 times the pertinent values in table 1, column 3 of appendix B to §§20.1001-20.2401 of this part. This type of respirator is not suitable for protection against plutonium or other high-toxicity materials. The mask is to be tested for fit prior to use, each time it is donned.

i. 1. Equipment shall be operated in a manner that ensures that proper air flow-rates are maintained. A protection factor of no more than 1000 may be utilized for tested-and-certified supplied-air hoods when a minimum air flow of 6 cubic feet (0.17 cubic meters) per minute is maintained and calibrated air-line pressure gauges or flow measuring devices are used. A protection factor of up to 2000 may be used for tested and certified hoods only when the air flow is maintained at the manufacturer's recommended maximum rate for the equipment, this rate is greater than 6 cubic feet (0.17 cubic meters) per minute, and calibrated air-line pressure gauges or flow measuring devices are used.

2. The design of the supplied-air hood or helmet (with a minimum flow of 6 cfm (0.17 m^3 per minute) of air) may determine its overall efficiency and the protection it provides. For example, some hoods aspirate contaminated air into the breathing zone when the wearer works with hands-over-head. This aspiration may be overcome if a short capelike extension to the hood is worn under a coat or overalls. Other limitations specified by the approval agency shall be considered before using a hood in certain types of atmospheres (see footnote *i*).

j. Appropriate protection factors shall be determined, taking into account the design of the suit and its permeability to the contaminant under conditions of use. There shall be a standby rescue person equipped with a respirator or other apparatus appropriate for the potential hazards and communications equipment whenever supplied-air suits are used.

k. No approval schedules are currently available for this equipment. Equipment is to be evaluated by testing or on a basis of reliable test information.

l. This type of respirator may provide greater protection and be used as an emergency device in unknown concentrations for protections against inhalation hazards. External radiation hazards and other limitations to permitted exposure, such as skin absorption, must be taken in to account in such circumstances.

m. Quantitative fit testing shall be performed on each individual and no more than 0.02% leakage is allowed with this type of apparatus. Perceptible outward leakage of gas from this or any positive pressure self-contained breathing apparatus is unacceptable because service life will be reduced substantially. Special training in the use of this type of apparatus shall be provided to the wearer.

Note 1: Protection factors for respirators as may be approved by the U.S. Bureau of Mines/National Institute for Occupational Safety and Health (NIOSH), according to applicable approvals for respirators for type and mode of use to protect against airborne radionuclides, may be used to the extent that they do not exceed the protection factors listed in this table. The protection factors listed in this table may not be appropriate to circumstances where chemical or other respiratory hazards exist in addition to radioactive hazards. The selection and use of respirators for such circumstances should take into account applicable approvals of the U.S. Bureau of Mines/NIOSH.

Note 2: Radioactive containments for which the concentration values in Table 1, Column 3 of Appendix B to §§20.1001-20.2401 of this part are based on internal dose due to inhalation may, in addition, present external exposure hazards at higher concentrations. Under these circumstances, limitations on occupancy may have to be governed by external dose limits.
[56 FR 23408, May 21, 1991. Redesignated at 58 FR 67659, Dec. 22, 1993]

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APPENDIX E

ELECTRONIC INPUT/OUTPUT FILES

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APPENDIX E - ELECTRONIC INPUT/OUTPUT FILES

SCALE V4.3V File Listing

The following is a directory listing of the SCALE V4.3V input and output files. Input files are identified by the extension *in*; output files are identified by the extension *out*. The first part of the filename identifies the exposure condition: infinite air slab (*airslab*), infinite plane (*infplane*), submersion in drifts (*subm*), surface contamination in drifts (*surf*). The drift is identified as main drift (*md*) or emplacement drift (*ed*). The number 1 in the filename identifies runs for the first 9 energy groups, while the number 2 identifies runs for the last 9 energy groups. All files are stored electronically on the CD-ROM disk included in this appendix.

```
 Volume in drive D is Comp Files
 Volume Serial Number is 3ACF-CB8C
 Directory of D:\Modeling for Airborne Contamination - Electronic Files\SCALE
Files

.              <DIR>         09-15-99  3:49p .
..             <DIR>         09-15-99  3:49p ..
AIRSLAB1 IN           2,784  07-19-99 10:38a airslab1.in
AIRSLAB1 OUT        694,069  07-19-99 10:52a airslab1.out
AIRSLAB2 IN           2,808  07-19-99 10:38a airslab2.in
AIRSLAB2 OUT        589,271  07-19-99 10:54a airslab2.out
GRND_ED1 IN           4,753  07-15-99 12:03p grnd_ed1.in
GRND_ED1 OUT        727,407  07-15-99 12:14p grnd_ed1.out
GRND_ED2 IN           4,776  07-15-99 12:04p grnd_ed2.in
GRND_ED2 OUT        662,246  07-15-99 12:15p grnd_ed2.out
GRND_MD1 IN           4,753  07-15-99 11:21a grnd_md1.in
GRND_MD1 OUT        727,407  07-15-99 12:08p grnd_md1.out
GRND_MD2 IN           4,776  07-15-99 12:06p grnd_md2.in
GRND_MD2 OUT        662,246  07-15-99 12:12p grnd_md2.out
INFPLANE IN           9,328  07-15-99 12:20p infplane.in
INFPLANE OUT      1,521,362  07-15-99 12:23p infplane.out
SUBM_ED1 IN           4,627  07-19-99 10:41a subm_ed1.in
SUBM_ED1 OUT        727,407  07-19-99 10:45a subm_ed1.out
SUBM_ED2 IN           4,650  07-19-99 10:41a subm_ed2.in
SUBM_ED2 OUT        662,430  07-19-99 10:47a subm_ed2.out
SUBM_MD1 IN           4,564  07-19-99 10:41a subm_md1.in
SUBM_MD1 OUT        727,407  07-19-99 10:48a subm_md1.out
SUBM_MD2 IN           4,587  07-19-99 10:42a subm_md2.in
SUBM_MD2 OUT        662,430  07-19-99 10:50a subm_md2.out
        22 file(s)       8,416,088 bytes
```

MCNP V4B2LV File Listing

The following is a directory listing of the MCNP V4B2LV input and output files. Input files are identified by the absence of an extension; output files are identified by the extension *out*. The first two letter of each file identify the radionuclide symbol (except iodine, with one letter); the last three letters identify the exposure condition (*air* for air submersion and *con* for surface contamination). All files are stored electronically on the CD-ROM disk included in this appendix.

```
 Volume in drive D is Comp Files
 Volume Serial Number is 3ACF-CB8C
 Directory of D:\Modeling for Airborne Contamination - Electronic Files\MCNP
Files

.              <DIR>        08-22-00  1:28p .
..             <DIR>        08-22-00  1:28p ..
AMAIR                 3,126  09-15-99 12:48p Amair
AMAIR    OUT         71,707  09-15-99  1:28p amair.out
AMCON                 3,145  09-15-99 12:56p Amcon
AMCON    OUT         54,569  09-15-99  1:48p amcon.out
BAAIR                 3,158  09-14-99  4:51p Baair
BAAIR    OUT         56,835  09-14-99  7:54p baair.out
BACON                 3,169  09-15-99  1:01p Bacon
BACON    OUT         55,810  09-15-99  4:29p bacon.out
COAIR                 3,090  09-14-99  4:47p coair
COAIR    OUT         51,465  09-14-99  6:13p coair.out
COCON                 3,103  09-15-99 12:58p cocon
COCON    OUT         49,795  09-15-99  2:49p cocon.out
CSAIR                 3,277  09-14-99  5:40p Csair
CSAIR    OUT         56,317  09-14-99  7:34p csair.out
CSCON                 3,294  09-15-99  1:00p Cscon
CSCON    OUT         50,065  09-15-99  4:09p cscon.out
DIR                   2,239  09-16-99  9:03a dir
EUAIR                 3,633  09-14-99  4:52p Euair
EUAIR    OUT         55,640  09-14-99  8:14p euair.out
EUCON                 3,640  09-15-99  1:01p Eucon
EUCON    OUT         52,485  09-15-99  4:49p eucon.out
IAIR                  3,137  09-15-99 12:50p Iair
IAIR     OUT         74,501  09-15-99  2:08p iair.out
ICON                  3,153  09-15-99 12:56p icon
ICON     OUT         58,374  09-15-99  2:28p icon.out
KRAIR                 3,058  09-15-99  7:22a krair
KRAIR    OUT         55,821  09-15-99  8:02a krair.out
KRCON                 2,996  09-15-99 12:59p krcon
KRCON    OUT         38,741  09-15-99  3:09p krcon.out
RHAIR                 3,181  09-14-99  4:49p Rhair
RHAIR    OUT         57,665  09-14-99  6:53p rhair.out
RHCON                 3,201  09-15-99 12:59p rhcon
RHCON    OUT         52,015  09-15-99  3:29p rhcon.out
SBAIR                 3,445  09-14-99  4:50p Sbair
SBAIR    OUT         59,163  09-14-99  7:13p sbair.out
SBCON                 3,466  09-15-99  1:00p Sbcon
SBCON    OUT         51,738  09-15-99  3:49p sbcon.out
        37 file(s)      1,063,217 bytes
```

Excel 97 File Listing

The following is a directory listing of the Excel 97 files described in Appendix C. All files are stored electronically on the CD-ROM disk included in this appendix.

```
 Volume in drive D is Comp Files
 Volume Serial Number is 3ACF-CB8C
 Directory of D:\Modeling for Airborne Contamination - Electronic Files\EXCEL
Files

.               <DIR>        08-22-00  2:17p .
..              <DIR>        08-22-00  2:17p ..
ANSI-A~6 XLS        121,856  08-22-00  3:55p ANSI-ANS-6.1.1.xls
RADION~8 XLS        123,392  08-22-00  3:29p Radionuclide DCF.xls
SUBME~10 XLS         98,304  08-22-00  3:42p Submersion DCF.xls
SURFA~12 XLS         99,328  08-22-00  3:50p Surface DCF.xls
         4 file(s)        442,880 bytes
```

OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
SPECIAL INSTRUCTION SHEET

1. QA: QA
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Complete Only Applicable Items

This is a placeholder page for records that cannot be scanned or microfilmed

2. Record Date 09/12/2000	3. Accession Number ATT-TO MOL.20000926.0233
4. Author Name(s) E. FAILACE	5. Author Organization N/A
6. Title MODELING FOR AIRBORNE CONTAMINATION	
7. Document Number(s) TDR-WER-NU-000003	8. Version REV. 0
9. Document Type ~~CD-ROM~~ DATA	10. Medium ~~DATA~~ ~~OPTIC~~ / DISK
11. Access Control Code PUB	
12. Traceability Designator DC #22109	
13. Comments THIS IS A SPECIAL PROCESS CD-ROM AND CAN BE LOCATED THROUGH THE RPC	